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Diatoms as Indicators of Eutrophication in Lakes, Pine Lake, Alberta, Canada: A Case Study

by

Shima Dorice Blakney

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

Department of Biological Sciences

Edmonton, Alberta

Spring 1998

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled DIATOMS AS INDICATORS OF EUTROPHICATION IN LAKES, PINE LAKE, ALBERTA, CANADA: A CASE STUDY, submitted by SHIMA DORICE BLAKNEY in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

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DATE: January 27, 1998

I would like to dedicate this thesis to my family, Amy, George, Barton, and Devere Blakney.

Your love and support has been and will always be invaluable.

ABSTRACT

Pine Lake, located 35km southeast of Red Deer (52°04'N 113°27'W), is one of Alberta's most intensively developed lakes, with historical removal of the catchment forest for agricultural, settlement, and recreational purposes. This change in catchment use has led to an increase in nutrient input to the lake. Lake sediments contain a wide variety of organisms including diatoms, unicellular algae sensitive to lake system changes. Duplicate short cores were collected from three sub-basins within the lake and analysed for loss on ignition, carbonates, water content, pigment and diatom composition. Non-parametric statistical analysis shows that all six lake cores are statistically similar both within the sub-basins and between the three sub-basins. The diatom taxa shifts from an assemblage dominated by *Cyclotella bodanica aff. lemanica*, an oligotrophic/mesotrophic species, before settlement, to a eutrophic assemblage, dominated by *Aulacoseira granulata*, at present. There is also a rise in myxoxanthophyll, a cyanobacterial pigment often associated with eutrophication. The results of this study indicate that anthropogenic stress has led to an increase of nutrient input into the lake which is detectable through both the diatom and the pigment record.

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1. INTRODUCTION

1.1 Palaeolimnological Applications

Palaeolimnology is the study of a lake's past history derived from changes in the ecosystem and the potential causes of those changes (Frey, 1988). It is a useful approach for evaluating limnological data in cases where direct human measurements are not available (Smol, 1992). Palaeolimnological techniques can be utilized to interpret past lake history by studying sequentially deposited sediments on the lake bottom (DeCosta & Warren, 1967). Lake sediments are derived from both external input from the watershed or catchment area, and from internal input through biogenic productivity (Birks & Birks, 1980). The organic and inorganic material that comprises the lake sediment can be analyzed and identified to assess variation in sediment composition through time. The decomposed organic matter includes predominantly resistant substances such as photosynthetic plant pigments, and chitin from insect exoskeletons. The inorganic fraction includes silica (SiO_2), the main component of diatom frustules (Birks & Birks, 1980). Analyzing both inorganic and organic matrix components in association with temporal and spatial diatom distribution provides an enhanced interpretation of lake history (Rawlence, 1984).

Humans can drastically alter the allochthonous material entering a lake system by modifying vegetation and soil in the catchment area of a lake (Fritz, 1989). The internal biota of the lake may correspondingly be altered or influenced by these changes in the catchment area. Variations in life assemblages through time within the lake are reflected by stratigraphic variation in fossil assemblages within the sediment column. Lake sediment

composition may therefore be utilized to determine past events that have occurred in the catchment area, and the effects that these changes have had on the lake environment.

Diatoms are considered to be one of the more useful parameters in assessing historical eutrophication and pollution of a lake (Alhonen, 1979). Diatoms are unicellular or colonial algae that possess a siliceous cell wall (Birks & Birks, 1980). After death these siliceous walls (frustules) become incorporated into the accumulating lake sediment where they are usually abundant and well preserved. They are not indestructable and have been found to dissolve under very alkaline conditions (Round, 1964). This is not considered a major factor in fossil diatom assemblages found in freshwater lakes, but can be a major factor in marine environments (Round, 1964). Conditions to which diatom species are sensitive include pH, salinity,climate, light and nutrient levels (Alhonen, 1971). Fossil diatom assemblages have proven useful in detecting recent changes caused by local human disturbance of watersheds (Charles, 1985).

Diatoms can be used both qualitatively and quantitatively in palaeoecological research. The earliest work using diatoms began with Hustedt (1937), when he grouped diatoms together based on the kind of water in which their presence was optimal and according to the hydrogen-ion concentration of the water (Merläinen, 1967). This approach is still utilized today, and is known as Hustedt's pH spectrum. The first quantitative use of diatom data occurred in a study by Nygaard (1956), emphasizing the ecological significance of extreme groups on the pH spectrum (Merläinen, 1967). Round (1957) correlated diatom data with known pollen stratigraphy of sediment cores. Using this data, he was able to show variations in lake productivity and community change using

the diatoms and was able to determine climate change using the pollen data. Finally, Haworth (1969) demonstrated qualitative conclusions on general lake ecology based on species changes throughout a core.

Smol (1985) demonstrated other qualitative methods by determining nutrient levels by comparing diatom valve to chrysophyte cyst ratios. High numbers of chrysophyte cysts relative to low numbers of diatom valves is suggestive of oligotrophic or nutrient poor water conditions. Comparisons have also been made between community types such as benthic versus planktonic diatoms. Depending on the dominant group one can then assess dissolved silica and nutrient concentrations as well as water levels in a given lake (Engstrom et al., 1991).

The use of calibration sets is a recent quantitative approach to palaeoecology (Smol & Glew, 1992). A set of lakes each possessing relevant lake water chemistry are chosen within a study region. The top 1cm of the sediment is sampled within each lake to determine the microfossils deposited within the last ~3 years. The microfossils are then correlated with lake water chemistry during the same time frame (Smol & Glew, 1992). Microfossils contained in these surface sediments are then identified and enumerated, providing diatom taxa in correlation to the measured limnological features of the lake. A calibration set is thus derived for diatom remains in deep water surface sediments from lakes with known lake chemistries. By utilizing this calibration set it is possible to infer past lake conditions by applying a set of equations to deep sediment diatom remains (Davis & Anderson, 1985). This technique has been found to be especially invaluable for assessing watershed land usage in recent decades and centuries (Davis & Anderson,

1985).

The usage of statistical calculations as a quantitative measure to infer limnological data has become important when conditions cannot be directly measured (Hall & Smol, 1992). Recently, a model involving multiple linear regression has been used to study lake trophic status (Whitmore, 1989). However, many shortcomings accompany the use of this model. One shortcoming is the unimodal response species have to environmental variables leading to inconsistencies in the assumption that diatom taxa and trophic status have a linear relationship (ter Braak & van Dam, 1989). Other problems include the high correlations of ecologically similar taxa, producing unstable coefficients of multiple linear regression equations, and the inevitable loss of vital ecological information due to the grouping of large numbers of taxa into smaller ecological categories (Hall & Smol, 1992).

Vast improvements in quantitative analysis have led to the development of direct gradient and unimodal statistical models based on weighted-averaging computational techniques (Hall & Smol, 1992). By using models such as canonical correspondence analysis (CCA) and weighted-averaging (WA) regression and calibration, the assumption can then be made that individual taxa respond in a unimodal manner over long environmental gradients. CCA has been used to determine the relationship between diatom distributions in surficial sediments to lake depth, nitrogen, phosphorous, and chlorophyll *a* concentrations (Christie, 1988). CCA has been thought to have potential in paleoecology because it allows land use/vegetation relationships to be studied directly and simultaneously (Birks et al., 1990). With all the advances in quantitative approaches to lake assessment, the stratigraphic (qualitative) approach remains strong in providing the

historical perspective necessary to evaluate human caused changes in lacustrine environments (Anderson, 1994).

Recently, diatom studies have concentrated on determining the natural state of lakes prior to human activity and utilising these findings in setting realistic goals for mitigation programs (Smol, 1992). Diatom plankton records are largely interpreted using indicator species and their commonly found associations (Stoermer, 1984) and can be applied both to track eutrophication through history and to assess lake response after nutrient reduction (Anderson et al., 1990). Reavie et al. (1995) utilised palaeolimnology to identify trophic changes that had occurred before conventional monitoring programs were initiated. More specifically, they relied on past diatom species composition as the chosen proxy method since diatoms are particularly sensitive to nutrient changes (Anderson & Rippey, 1994). It was found that the diatom community shifted to a more eutrophic composition as anthropogenic nutrient enhancement occurred in the Okanagan Valley (Christie & Smol, 1993). The land surrounding Wood Lake, within the Okanagan Valley, was initially cleared and developed for agricultural purposes. More recently, summer homes and residential developments have started to dominate the southern lake shore (Walker et al., 1993). Walker et al. (1993) used the diatom population to track eutrophication. Since initial European settlement, they found that marked changes in diatom population composition occurred within the lake cores. As the use of pesticides and chemical fertilizers increased, the algal composition shifted significantly towards eutrophy.

The diatom record coupled with pigment analyses provides a more accurate

characterization of population dynamics resulting from shifts in land use and increases in anthropogenic activity (Millie et al., 1993). Fossil pigments have been studied in freshwater lakes for more than 30 years, beginning with the observation that both chlorophyll derivatives and carotenoids were universally present in both surface sediments and in older core material (Sanger, 1988). Although pigments are useful in inferring past lake productivity and trophic levels, several problems are apparent. Included in these are the selective destruction of the more labile pigments and an inability to distinguish between allochthonous and autochthonous input (Sanger, 1988). Selective preservation remains problematic when dealing with certain groups of algae. Diatom and chrysophyte pigments (chlorophyll *c*, fucoxanthin, diadinoxanthin) have been found to be more labile than pigments from green algae (lutein, chlorophyll *b*), cyanobacteria (myxoxanthophyll, zeaxanthin), and cryptophytes (alloxanthin, alpha-carotene, *a*-phorbins) (Leavitt, 1993). As a group, the carotenoids have demonstrated a better correlation to lake productivity than chlorophyll derivatives, even though both groups are better preserved in eutrophic than oligotrophic lakes (Sanger, 1988). Sedimentary pigments may yield information relevant to past lake trophic state by identifying indicator pigments which have taxonomic specificity (Züllig, 1989). Past studies dealing with increased nutrient input in response to human settlement, forest clearance and agricultural fertilization, have found a dramatic rise in cyanobacterial carotenoids, myxoxanthophyll and oscillaxanthin (Griffiths, 1978). More recent studies, such as one in the English Lake district (Meyers & Ishiwatari, 1993) used carotenoid pigments associated with cyanophytes to trace progressive eutrophication. Since prokaryotic organisms can outcompete aquatic eukaryotes in turbid, nutrient rich

waters, cyanobacterial populations should be monitored (Sanger, 1988). Other factors which effect pigment preservation, include oxygen concentration in the water column, basin depth, sedimentation rates, water temperature and light conditions (Sanger, 1988). In spite of these problems it is still possible to identify the main changes within algal group populations by comparing historical records with the within-core changes of individual pigments (Hurley et al., 1992).

Several past studies of Alberta lakes have analyzed changes in diatom communities and pigment concentrations through time. Baptiste Lake, a central Alberta lake, appears to have become more eutrophic with time. A succession of diatom species takes place with the final dominant being *Aulacoseira granulata* , a species known for growing well in strongly eutrophic conditions (Hickman et al., 1990). Palaeoproduction has been studied using sedimentary chlorophyll *a* and total carotenoid derivatives for both Lake Wabamun (Hickman & Schweger, 1991) and Moore Lake (Hickman & Schweger, 1996). Peaks in the blue-green algal population indicate an increase in lake production in association with an increase in nutrient input (Hickman & Schweger 1991; Hickman & Schweger 1996). Past investigations of Alberta lakes have concentrated primarily on assessing long-term changes in lake history including climate and past lake production. This study comprises an analysis coupling land use history with the diatom communities and the pigment fluctuations in an Alberta lake.

1.2 The Pine Lake Project

Human disturbance upsets the natural functioning of an ecosystem. Pine Lake with its abundance of trailer parks, summer homes, and cottages, as well as farm land has definitely been under the influence of humans both past and present. The purpose of this study is to determine the effects that land use has had on the natural biota of the lake, specifically on the diatom communities.

Pine Lake is currently eutrophic. It is probable that the natural process of eutrophication has been accelerated due to humans changing the natural conditions of the lake (Alhonen, 1979). Cultural eutrophication has been shown to exhibit characteristics such as high nutrient levels, increased production of plankton and an oxygen deficit in the hypolimnion (Alhonen, 1979). These characteristics may all be observed in Pine Lake today.

Palaeolimnological studies are important in determining the extent to which anthropogenic stress alters an ecosystem over time. Diatoms and sedimentary pigments, assessed in association with historical data should enable the following questions to be answered about Pine Lake: Has the lake always been eutrophic or is this a recent development? Does the diatom population respond to the increased pollution by exhibiting a shift in dominant taxa? Is there a reduction in species diversity with increased productivity? Does the blue-green algal population show an increase in the pigment record associated with increased productivity? If there is an increase in blue-green algae and other planktonic populations, is there also a shift to spring and fall blooming species which can not out-compete the dominant populations that prosper in the middle summer?

Figure 1. Bathymetric map of Pine Lake, Alberta showing study site core locations. Adapted from Alberta Environment, 1992 Hydrographic Survey. Depth in metres.

2. SITE DESCRIPTION

2.1 Physical Lake & Catchment Characteristics

Pine Lake, Alberta (52° 04'N 113° 27'W) is located approximately 35km southeast of the city of Red Deer (Figure 1). It has a maximum length and width of 6.4 and 0.8km, respectively. It lies in a narrow glacial meltwater channel and comprises 3 sub-basins; a north sub-basin with a maximum depth of 8.8m, a south sub-basin with a maximum depth of 12.8m, and a central sub-basin with a maximum depth of 13.2m. The surface area of the lake is 3.89km^2, with a drainage basin almost 40x the area of the lake. The volume of Pine Lake has increased since 1990 from 20.6 x 10^6 to 24.1 x 10^6m^3, with an increased maximum depth of 13.2m from 12.2m (Sosiak & Trew, 1996). In the northwest portion of the basin, the moraine is hummocky with a knob and kettle terrain. The majority of the runoff is trapped in these potholes and rarely reaches Pine Lake. The effective basin is therefore probably smaller than the apparent one. The lake is fed by several intermittent streams, the majority of which enter the northern half of the lake. An outlet stream, Ghostpine Creek, flows out the south end of the lake, entering the Red Deer River near the city of Drumheller. Ghostpine Creek generally has a strong flow during spring runoff but often dries up by early summer when water is retained by the numerous beaver dams upstream (Sosiak & Trew, 1996). The substratum in the littoral zone comprises primarily sand and/or gravel (Hamilton, 1980). Erosion has occurred along the shoreline in several locations, and berms have been installed to slow the process. The estimated residence time of water in the lake is approximately 9 years (Mitchell & Prepas, 1990).

The bedrock is Paskapoo Formation (Paleocene) consisting of interbedded

sandstone, siltstone, mudstone, and thin limestone layers, which, in most of the lake basin, underlies glacial till. The lake is bordered by outcrops on some of the steep slopes and escarpments (Pedol. Consult. 1980). The soils are typically well-drained, orthic, dark brown and black chernozemics, and dark gray chernozemics, with gleysols in low-lying, poorly drained areas. The wet, sedge-marsh areas consist of organic-rich soils (Strong & Leggat, 1981). Pine Lake is located in the Groveland subregion of Aspen Parkland. The dominant vegetation found surrounding the lake is dependent upon the aspect of the slope. On the south facing areas, some north slopes and level areas, the dominant or native vegetation consists primarily of rough fescue grass (*Festuca altaica*) and aspen (*Populus*) dominated woodlands. Whitespruce (*Picea glauca*) grows on the majority of north facing slopes, with willow (*Salix* sp.) and sedge (*Carex* sp.) dominating the wetlands. The macrophyte community, both submergent and emergent, in Pine Lake is extensive in all areas of the lake, with the exception of a few rocky areas in the southern portion of the lake (Mitchell & Prepas, 1990). The dominant species of submergent macrophytes include Northern watermilfoil (*Myriophyllum exalbescens* Fern), large-sheath pondweed (*Potamogeton vaginatus* Turcz), and Richardson pondweed (*P. richardsonii* (Benn) Rydb). The emergent macrophytes are comprised primarily of cattail (*Typha latifolia*) and to a lesser extent, bulrush (*Scirpus* sp.), arrowhead (*Sagittaria* sp.), and sedge (*Carex* sp.), all of which are found mostly along the western shore of Pine Lake (Mitchell & Prepas, 1990). The Pine Lake blue-green algal population is dominated by *Aphanizomenon flos-aquae* (L) Ralfs, *Anabaena lemmermanii* P. Richter, and *Microcystis aeruginosa* Kütz.emend. Elenkin (Watson, 1993), all of which are characteristic of highly

eutrophic systems (Sosiak & Trew, 1996).

Pine Lake is a well-buffered, freshwater lake with bicarbonate and sodium as the dominant ions (Table 1). Pine Lake becomes thermally and chemically stratified during the summer resulting in hypolimnetic oxygen depletion. During windy periods stratification is broken and the hypolimnetic waters become replenished with oxygen. Fishkills due to anoxia are not a problem due to high dissolved oxygen concentrations in the upper portion of the water column (Hamilton 1980), both in the summertime and wintertime. During the winter, bacterial decomposition of organic matter in the bottom sediments depletes dissolved oxygen near the bottom, while high concentrations of dissolved oxygen are maintained in the upper water column. Throughout the summer Total Phosphorous (TP) concentration increases due to internal release of phosphorous from the lake sediments especially during anoxic periods. Compared to phosphorous levels, nitrogen was relatively low, a factor that probably favours blue-green algal blooms (Sosiak & Trew, 1996). This was confirmed by Watson (1993), who found low numbers of heterocysts associated with the blue-green nitrogen fixing species, indicating that nitrogen was not a limiting factor at this time.

2.2 Pine Lake Settlement and Land Use, 1850 to present

Prior to the 1850's travel by non-Indians through the Red Deer Parkland area, including Pine Lake, was minimal (Batchelor, 1978). Between 1890 and 1900, there was increased activity around Pine Lake as the first European settlers arrived (Elnora Hist. Commit., 1972), at which time a post office and a trading post were established at the lake

Table 1. Major ions and related water quality variables for Pine Lake. Average concentrations in mg/L; pH in pH units. The major ions adapted from Sosiak & Trew (1996) are based on euphotic samples collected in 1992. Related water quality variables adapted from Alberta Environment (n.d.a) are based on composite samples from the euphotic zone collected from July 12 to September 17, 1984.

	MEAN
pH	7.9-8.9
total alkalinity ($CaCO_3$)	319
specific conductivity (calculated)	726
total dissolved solids (calculated)	450
total hardness ($CaCO_3$)	160
HCO_3	362.4
CO_3	12.5
Mg	25.0
Na	99.0
K	9.5
Cl	7.0
SO_4	68.8
Ca	25.6

(Elnora Hist. Commit., 1972). The increase in white settlers around Pine Lake was due, in part, to the completion of the railway north from Calgary in 1891 (Elnora Hist. Commit., 1972). According to Lawrence (1977) with this increase of human activity, the shoreline of Pine Lake was denuded and creek beds, draining both into, and out of, the lake, were increasingly found to be dry. Ranching was the dominant activity in the Pine Lake catchment and was characterized by particularly extensive use of the land (Batchelor, 1978). Research in the 1920's revealed that many of the aspen stands were of a single age and dated from 1908 - 1919, due to a period of colonization when much land was cleared or burned and subsequently abandoned (Batchelor, 1978). A relative shift from extensive to intensive regional and intra-farm use occurred during 1884 - 1914. However, lack of capital, the constraints of horse farming, large amounts of unoccuppied land, and uncertain trends in the economy led to an inhibition of regional economic development at this time (Batchelor, 1978).

Beginning in 1970, the water quality of Pine Lake increasingly became a concern to recreational users of the lake (Red Deer Reg. Plan. Commis., 1977). From 1978 to 1984 Pine Lake water quality, despite rising water levels, had decreased. By 1984, 35% of the shoreline had been developed into camping and commercial facilities. By 1988, 50% of the basin had been cleared for agriculture, primarily cereal crop production and mixed farming, and 1% developed for commercial use, mostly along the shoreline. A preliminary study completed by Alberta Environment in 1987, found that pollutants were draining into the lake from both mixed agricultural land, and septic system input from the various commercial developments. Between 1978 and 1994, an upward trend in total

phosphorous (TP) was observed. Blue-green algae were found in high numbers, due in part to the high phosphorous concentration in the water column, and to the low dissolved oxygen concentration occurring just above the sediment - water interface (Trimbee & Prepas, 1987; 1988). Phosphorous exchange between the bottom sediments and the overlying water is a third source of phosphorous within Pine Lake (Sosiak & Trew, 1996).

In 1992, it was estimated that there were approximately 112 private homes and cabins close to the lake, 11 farms adjoining the lake, 6 commercial campgrounds accommodating approximately 5000 persons most summer weekends, 3 institutional campgrounds, a service station, 2 stores, a postoffice, a community centre and various churches (Sosiak & Trew, 1996). Pine Lake is officially designated a non-public lake due to the limited public access and facilities. However, of the estimated 6000 persons using the lake on most weekends during the summer, 5000 or more do not have permanent facilities (Figure 2). It is estimated that utilization of commercial resorts, campgrounds, and institutional camps comprises 300,000 user-days per year and use of seasonal cottages and permanent residences comprises 37,350 user-days per year (Sosiak & Trew, 1996).

At present, Pine Lake is bordering on eutrophic/hypereutrophic conditions with greater than 100μg/L of Total Phosphorous (TP). Pine Lake residents, along with the Alberta Environmental Protection Agency, have instigated a lake restoration program, targeting the levels of phosphorous and the sources contributing to the increased phosphorous levels (Sosiak & Trew, 1996).

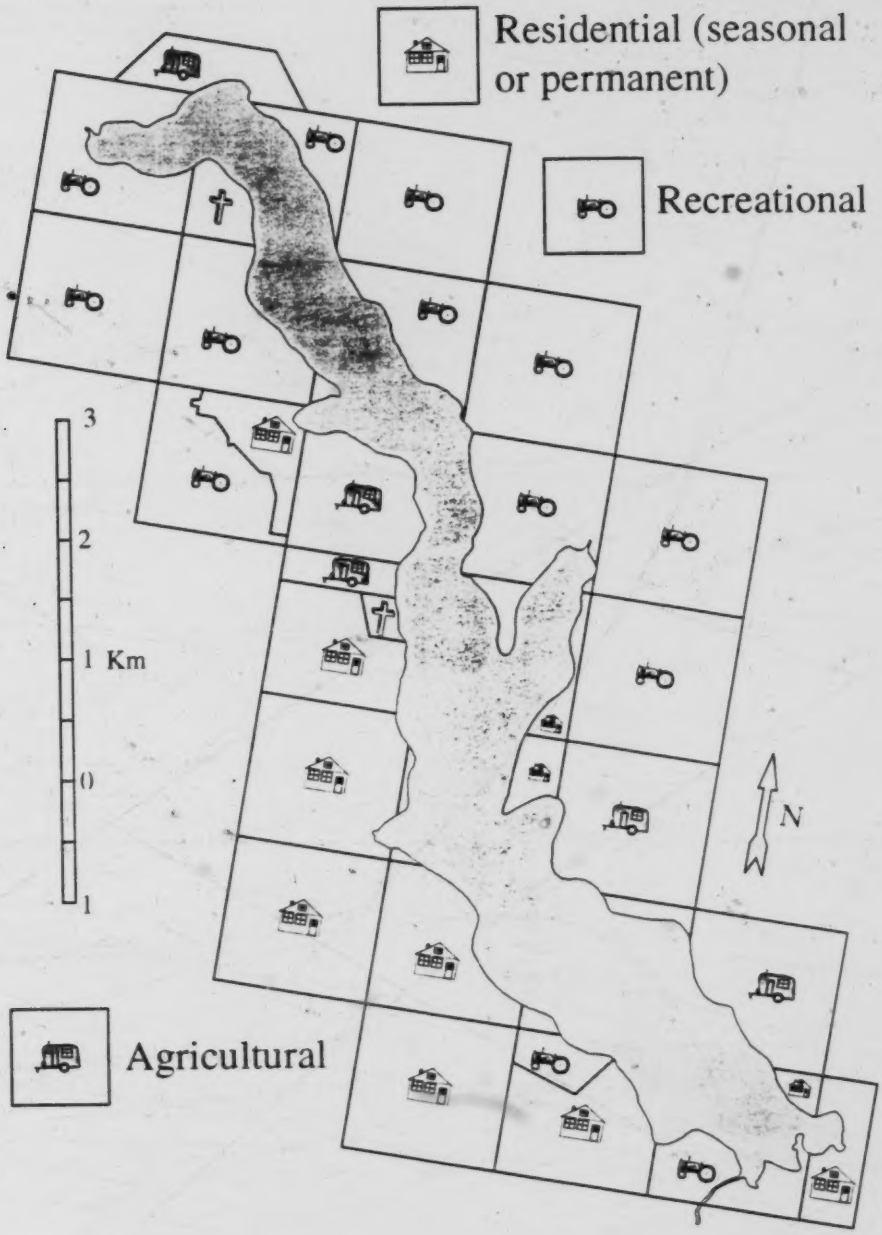


Figure 2. Map of Pine Lake, Alberta showing present day distribution of dominant land uses.

3. MATERIALS & METHODS

3.1 Coring Procedure

In order to study variability between sub-basins, six short sediment cores were extracted from Pine Lake in late October 1993, two cores from each of the 3 lake sub-basins. Duplicate cores from approximately the deepest regions were taken from the north sub-basin, the south sub-basin, and the central region of the lake (NCI, NCII, SCI, SCII, CCI, CCII), in order to assess within sub-basin variability. The coring device used was a technical operations corer (Mawhinney & Bisutti, 1987), which is a combination of a Benthos Gravity Corer and a Kajak-Brinkhurst Corer. It is lightweight and manually operated with a winch. The sediments were collected in 10cm diameter, 1m lengths of pvc plastic piping, capped and transported to the Alberta Environment Laboratories where they were stored upright at 10°C.

The sediments were vertically extruded, using pressurized water to drive the core upwards, and sliced into contiguous 0.5cm samples. The sediment samples were then placed in ziploc freezer bags and transported to the University of Alberta where they were stored at 0°C.

An additional lake core, a frozen finger core, taken by Dr. Ian Campbell at Canadian Forest Service was included in the diatom analysis (South Core III - SCIII).

3.2 Analytical Methodology

3.2.1 Water Content, LOI (Organic Matter), & Carbonates

Sampling procedures utilized here followed Wetzel (1970) with 1cm^3 sub-samples

taken for every 0.5cm sample on all six cores for analysis of organic matter, water and carbonate content. The water content was measured by placing the pre-weighed fresh sediment sub-samples in a drying oven for 24 hours and subtracting the weight of the residue from the initial weight. The organic matter was determined as loss on ignition after burning at 550°C for 1 hour and finally, carbonates were measured by further ignition at 950°C for 3 hours.

3.2.2 Diatom Analysis

The methodology outlined in Hickman & Klarer (1981) was employed to analyse the sediments for diatoms. A $1cm^3$ sub-sample was taken from each 0.5cm sample and treated with concentrated hydrochloric acid to dissolve the inorganic carbonate fraction. The acid was washed away with deionized water for a 7 day period or until a litmus test indicated neutral to alkaline conditions. The sub-samples were then treated with potassium dichromate and concentrated sulphuric acid to oxidize the organic matter. Again the sediments were washed with deionized water to remove all traces of acid solution, taking approximately 10 days.

Slide preparation also followed Hickman & Klarer (1981). A known volume was pipetted onto a coverglass and air dried over a 24 hour period. The coverslips were then placed on a warming tray set on high and left overnight to remove any trace amounts of water. The coverslips were then mounted in Eukitt, passed through a flame to drive off the toluene and air dried for a 24 hour period.

Diatom counts were done at 5.0cm intervals. In most cases, a minimum of 500

valves were counted at each level for all 7 cores (SCI, SCII, SCIII, NCI, NCII, CCI, CCII). *Asterionella formosa* Hassall was the only broken diatom included in the counts due to its abundance. In these cases, only diatoms with the larger apical inflation were counted to ensure that double counting of the same valve did not occur.

Diatom identification was based on Germain (1981), Hustedt (1930), and Krammer & Lange-Bertalot (1986). The percent distribution of each species was calculated, and species that had a presence greater than 1% were then graphed and used in the population totals. A diatom:cyst ratio was also calculated, utilizing all diatom species found. (Diatom species information including taxonomy, habitat and nutrient preference are included in Appendix I.)

3.2.3 Pigment Analysis

Central Core II (CCII) was chosen for pigment analysis because it was taken from an area of the lake which experienced a longer anoxic period and a larger total algal biomass than the other sub-basins (Watson, 1993). Based on these facts, better pigment preservation was expected in this area of Pine Lake.

One cm^3 sub-samples were taken from each 5.0cm sample, stored in plastic scintillation vials and freeze dried. Sub-samples were taken from the freeze dried sediments, weighed and placed into glass vials. Seven ml of extraction solvent (80acetone:15methanol:5water) was added to the sub-samples. The vials were then capped with nitrogen to prevent further pigment degradation following the methodology of Leavitt & Brown (1988). The sub-samples were then stored for 24 hours at 10°C to

allow for complete extraction.

The extraction solvent plus pigment was decanted off the sediment and transferred to a beaker. The remaining sediments were washed with 2cc of acetone (HPLC-Grade) which was then added to the beaker. The glass vial containing the sediments was then discarded. Using a 5cc syringe, the contents of the beaker were put through an Acrodisc 0.2μm syringe filter into a glass vial to remove all traces of sediment. The vials were placed under a nitrogen stream to dry the pigments. The dried pigments were then dissolved in a mixture of acetone, ion-pairing reagent (IPR), and methanol (70:20:10 by volume). Five hundred μl of this injection solvent was added to each vial. A 200μl sub-sample of this solution was transferred into coiled vials using a micropipette. The samples were stored at 10°C until they were run through the HPLC.

The quantification of pigment concentrations using reversed-phase high pressure liquid chromatography (RP-HPLC) followed the system preparation and execution methodology outlined in Leavitt, Carpenter & Kitchell (1989). The analytical pigment separation was achieved by isocratic delivery of mobile phase A (10% IPR in methanol) for 1.5 minutes, followed by a linear ramp to 100% B (27% acetonic methanol) over 7 minutes, and an isocratic hold for an additional 12.5 minutes. Re-equilibration of the column between samples was accomplished by linear ramping to 100% A over 7 minutes and maintenance for 45 minutes before sample injection (Leavitt, Carpenter & Kitchell, 1989).

3.3 Dating and Statistical Methodology

3.3.1 Pb^{210} Dates

Dr. Ian Campbell from Canadian Forest Service took a frozen finger core from the deepest point in the south sub-basin of Pine Lake (SCIII). Samples from this core were submitted to Flett Research (Winnipeg) for Pb^{210} analysis (Table 2). These dates were transferred to the other lake cores by subjective biostratigraphic correlation of the cores and reinforced by statistical analyses.

3.3.2 Core Correlation, inter- and intra-core variability

Two nonparametric statistical methods were employed to look at core similarities both within each individual sub-basin and among the 3 sub-basins. The Mann-Whitney Test and the Kendall Coefficient of Concordance were used to quantitatively correlate the 7 sediment cores.

The Mann-Whitney test (Seigel, 1988; Zar, 1984) determines whether 2 independent samples are drawn from the same population. This test was applied to duplicate and triplicate cores within a sub-basin to assess core similarity based on diatom populations within a site.

The Kendall Coefficient of Concordance (Seigel, 1988) is a measure of correlation between several data sets. The 7 sediment cores were simultaneously tested to assess the degree of association between sub-basins.

Both of these methods utilised ranked diatom species data in an interval-by-interval manner (Appendix II & III provides statistical formulae and sample calculations).

Table 2. Pb^{210} dates for South Core III (Campbell, 1996)

DEPTH (CM)	Pb^{210} Years	Pb^{210} AGE (Years)
0	0	1993
1.5	2	1991
3.5	7	1986
5.5	10	1983
7.5	15	1978
9.5	20	1973
13	28	1965
18	40	1953
23	53	1940
28.5	67	1926
40.5	105	1888
60.5	192	1801
71	248	1745

Table 3. Dates inferred using linear interpolation between Pb^{210} dates, South Core III. 23
There are no known dates below 70cm.

DEPTH (CM)	INFERRED AGE (YRS.)	ACTUAL YEAR (CA.)
0	0	1993
5	9	1984
10	21	1972
15	32.5	1961
20	45	1948
25	58	1935
27	63	1930
30	71	1922
35	87	1906
40	103	1890
45	124	1869
50	146	1847
55	167	1826
60	189	1804
65	215	1778
70	242	1751

4. RESULTS

4.1 Core Chronology

4.1.1 Pb^{210} Dating

Pine Lake South Core III (taken by Dr. Ian Campbell at Canadian Forest Service) was dated using the Pb^{210} technique. The core length of 0-71cm, covers the time interval from 1993 to 1745, respectively (Table 2). Core chronology was determined using linear interpolation between the Pb210 dates.

4.2 South Sub-Basin (SCI, SCII, SCIII* diatoms only)

4.2.1 Water Content (%)

South Core I (0-65.0cm) shows a gradual increase in water content with decreasing core depth. A maximum value of 94% is reached ca. 1993 (Figure 3).

South Core II (0-72.0cm) like SCI shows a gradual increase towards the top of the core, with the maximum value of 98.5% occurring ca. 1993 (Figure 4).

4.2.2 Loss-On-Ignition (% Organic Matter)

Overall, both SCI and SCII show an increase in percent organic matter towards the top of the core (Figures 3 & 4). SCI increases from 16.5% at the bottom of the core to 26% at the sediment water interface with a peak value of 27.5% ca. 1847. SCII has its minimum value of 17.1% ca. 1804 and a maximum value of 37.5% ca. 1993. The peak value seen in SCI is not present in SCII.

Figure 3: South Core I, Sediment Water, Organic & Carbonate Content
Pine Lake, Alberta, Canada

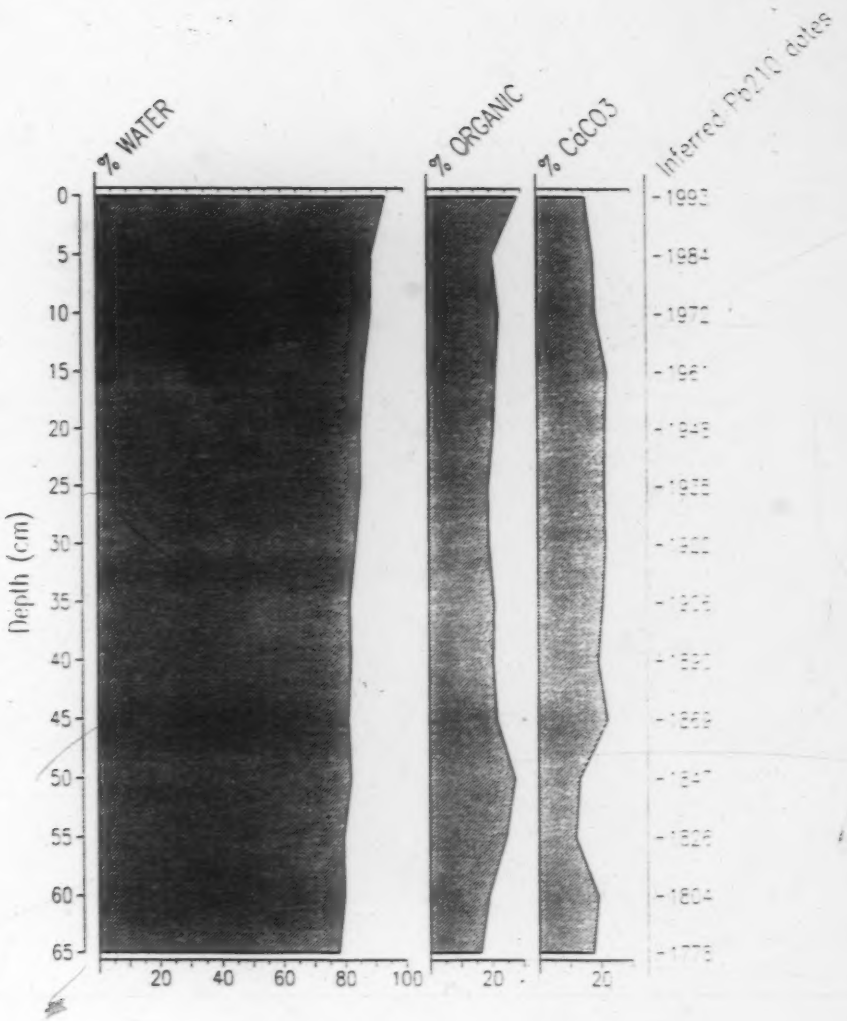
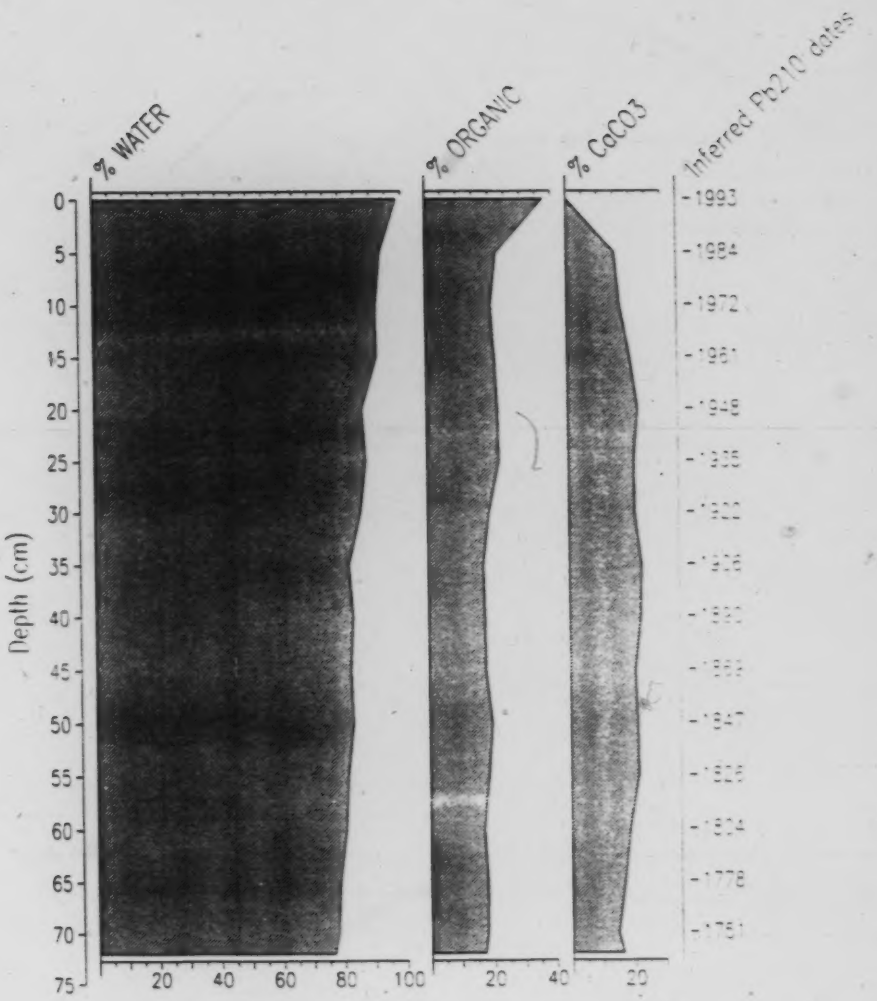

% WATER
% ORGANIC
% CaCO3
Inferred Pb210 dates
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
20
40
60
80
100
20
20
-1993
-1984
-1972
-1961
-1948
-1938
-1922
-1908
-1892
-1868
-1847
-1826
-1804
-1778

Figure 4: South Core II, Sediment Water, Organic & Carbonate Content
Pine Lake, Alberta, Canada


% WATER
% ORGANIC
% CaCO3
Inferred Pb210 dates
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
20
40
60
80
100
20
40
20
-1993
-1984
-1972
-1961
-1948
-1935
-1922
-1909
-1896
-1883
-1847
-1808
-1804
-1778
-1751

4.2.3 Carbonate Content (%)

The carbonate content in SCI appears to increase from ca. 1778 to ca 1804. A sharp decline occurs above 60.0cm, reaching minimum values of 12.1% and 13.3% at ca. 1826 and ca. 1847 respectively. After ca. 1847 carbonate increases, reaching a maximum value of 22.3% ca. 1869. From this point, to the top of the core, carbonate content gradually declines (Figure 3).

SCII shows a more constant level of carbonate composition until ca. 1984, at which point it sharply declines, reaching a minimum of 0% ca. 1993.

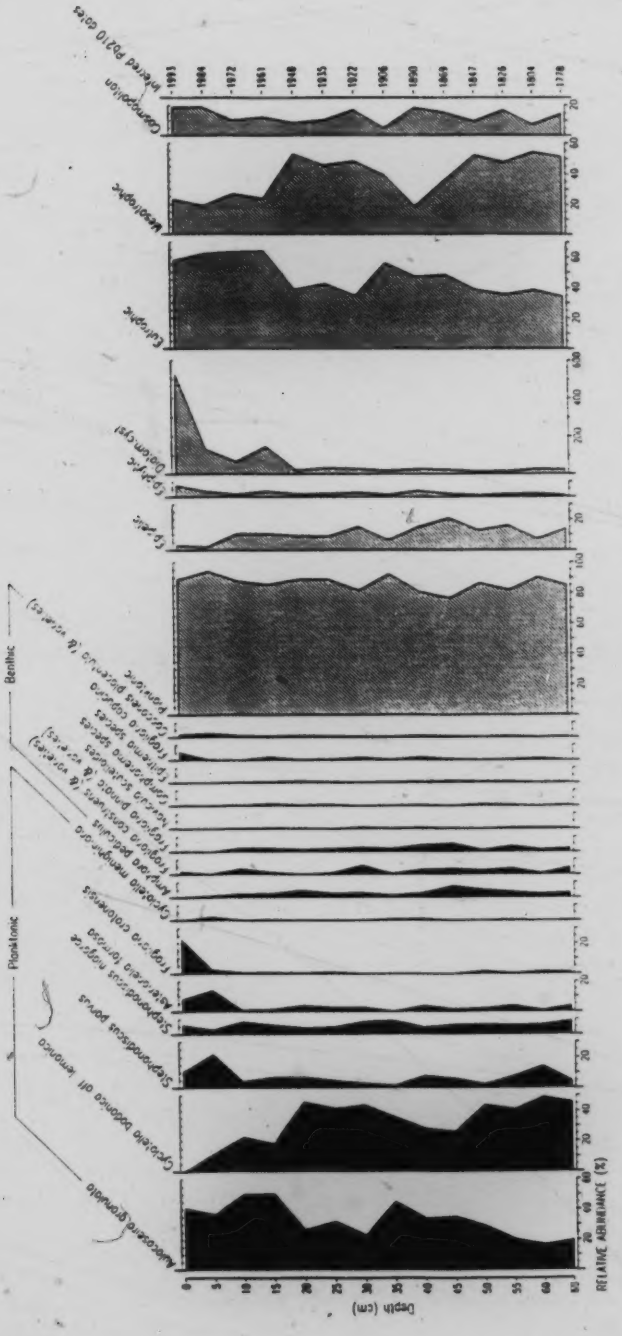
4.2.4 Diatom Composition

4.2.4.1 South Core I (0-65.0cm)

Cyclotella bodanica aff. *lemanica* dominates between ca. 1778 and ca. 1948 with a maximum abundance at ca. 1906 (Figure 5). Afterwards, it declines in prominence and is not present in the surface sample. This species has been gradually replaced by *Aulacoseira granulata* over the last 45 years, reaching its maximum abundance at ca. 1972 and ca. 1961 (49%). Other important species include *Stephanodiscus parvus* and *Asterionella formosa* which reach their maxima ca. 1984. *Fragilaria crotonensis* is present in minute amounts until ca. 1984 after which it blooms and *Stephanodiscus niagarae* is present in consistent quantities throughout the length of the core.

Eutrophic diatom species gradually increase towards the top of the core (Figure 9). They dominate between ca. 1948 and ca. 1993, while mesotrophic species are most important between ca. 1778 to ca. 1948.

Figure 5: South Core I, Diatom Composition
Pine Lake, Alberta, Canada


Planktonic
Benthic
Depth (cm)
RELATIVE ABUNDANCE (%)

The dominant community for SCI is planktonic (73.0-91.0%). Epipelic diatoms are present throughout the core, although they decline during the last 21 years. Epiphytic diatoms are present in low abundances (1.0-7.0%). They start to increase ca. 1972, reaching their maximum ca. 1993.

The diatom:cyst ratio remains relatively low prior to ca. 1948, at which point it sharply increases towards the top of the core.

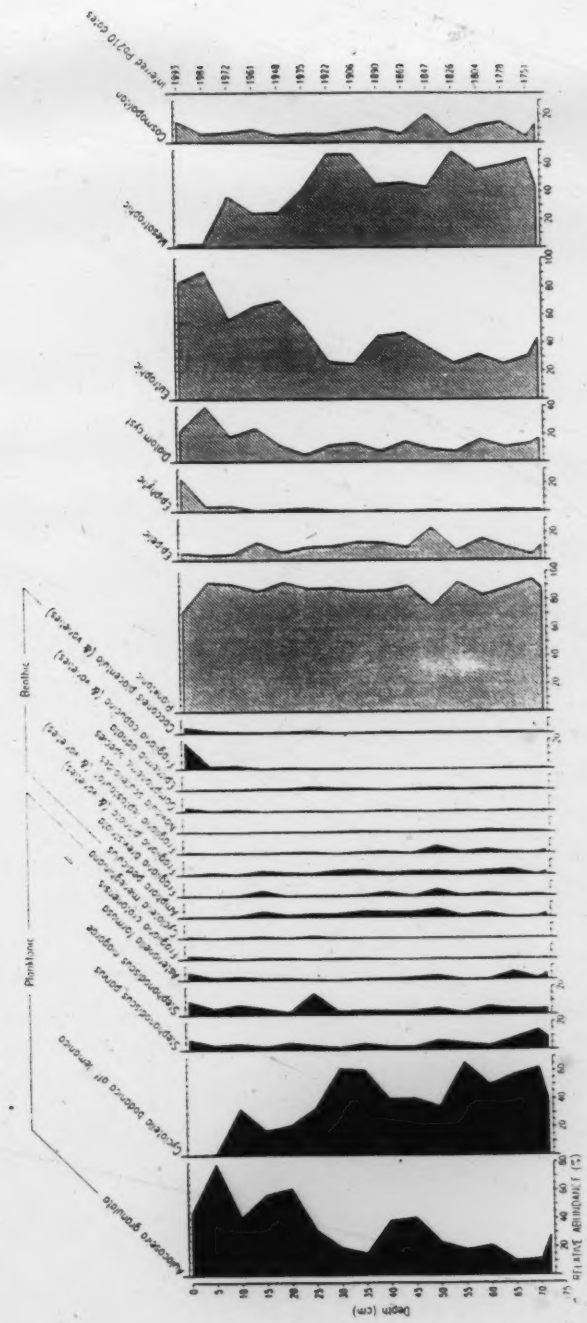
4.2.4.2 South Core II (0-72.0cm)

Cyclotella bodanica aff. *lemanica* dominates from the base of the core (ca. 1751) until ca. 1922, at which point it starts to decline, and is present in only negligible amounts at the top of the core (Figure 6). *Aulacoseira granulata* replaces *Cyclotella bodanica* aff. *lemanica* as the dominant taxon from ca. 1906 until the surface sample. Species which are present in relatively consistent proportions throughout the core include *Stephanodiscus niagarae* which reaches its maximum of 16.0% ca. 1935 and *Stephanodiscus parvus*, reaching its maximum of 15.0% ca. 1751. *Fragilara capucina* is rare to absent throughout most of the core, except in the surface sample where it reaches a maximum of 18.0%.

Mesotrophic diatoms dominate in abundance until ca. 1922, when they are replaced by eutrophic diatoms in the upper portion of the core.

Planktonic diatoms are abundant throughout the core (70.0-94.0%0). Epipelic diatoms decrease in abundance and are replaced by epiphytes from ca. 1961 until ca. 1993 (surface sample).

Figure 6: South Core II, Diatom Composition
Pine Lake, Alberta, Canada


Depth (cm)
Planktonic
Benthic
Cyclotella bodanica var. lemanica
Stephanodiscus parvus
Stephanodiscus neoastraea
Fragilaria crotonensis
Asterionella formosa
Fragilaria construens var. venter
Fragilaria construens var. binodis
Fragilaria construens var. construens
Fragilaria capucina var. rumpens
Fragilaria capucina var. capucina
Fragilaria capucina var. vaucheriae
Fragilaria capucina var. gracilis
Fragilaria capucina var. mesolepta
Fragilaria capucina var. capucina
Fragilaria capucina var. amphicephala
Fragilaria capucina var. acus
Fragilaria capucina var. radians
Fragilaria capucina var. dubia
Cocconeis placentula var. euglypta
Cocconeis placentula var. lineata
Achnanthes minutissima
Epithemia sorex
Epithemia turgida
Rhopalodia gibba
Diatoma vulgare
Tabellaria flocculosa
Melosira varians
Cyclotella comensis
Cyclotella bodanica var. lemanica
Asterionella ralfsii
Fragilaria crotonensis
Stephanodiscus parvus
Stephanodiscus neoastraea
Cyclotella bodanica var. lemanica
Asterionella formosa

The diatom:cyst ratio shows a gradual increase towards the top of the core.

4.2.4.3 South Core III (1-70.0cm)

Cyclotella bodanica aff. *lemanica* dominates from ca. 1751 to ca. 1906, declining in the past 87 years of the core to reach its minimum of 21.3% ca. 1993 (Figure 7). *Aulacoseira granulata* replaces *Cyclotella bodanica* aff. *lemanica* during the last 87 years to become the dominant. Diatom species that are present throughout the core include *Stephanodiscus parvus*, *Stephanodiscus niagarae*, and *Fragilaria capucina*. Both *Stephanodiscus parvus* and *Fragilaria capucina* reach their maxima ca. 1993 whereas *Stephanodiscus niagarae* reaches its minimum at this time.

Mesotrophic diatom species are dominant until ca. 1906 when they are gradually replaced by eutrophic diatom species in the past 58 years of the core.

The dominant community type is planktonic (80-90%) with much smaller epipelic (5-15%) and epiphytic (0-9%) communities.

The diatom:cyst ratio shows a gradual decline from ca. 1751 to ca. 1984 where it shows an abrupt and prominent increase to a maximum of 759:14 in ca. 1993.

4.3 North Sub-Basin (NCI & NCII)

4.3.1 Water Content (%)

Both North Core I (0-76.0cm) and North Core II (0-47.5cm) show an increase in water content towards the top of the core. NCI reaches a maximum value of 94.7% ca. 1993 and NCII a maximum value of 94.5% ca. 1993 (Figures 8 & 9).

Figure 7: South Core III, Diatom Composition
Pine Lake, Alberta, Canada

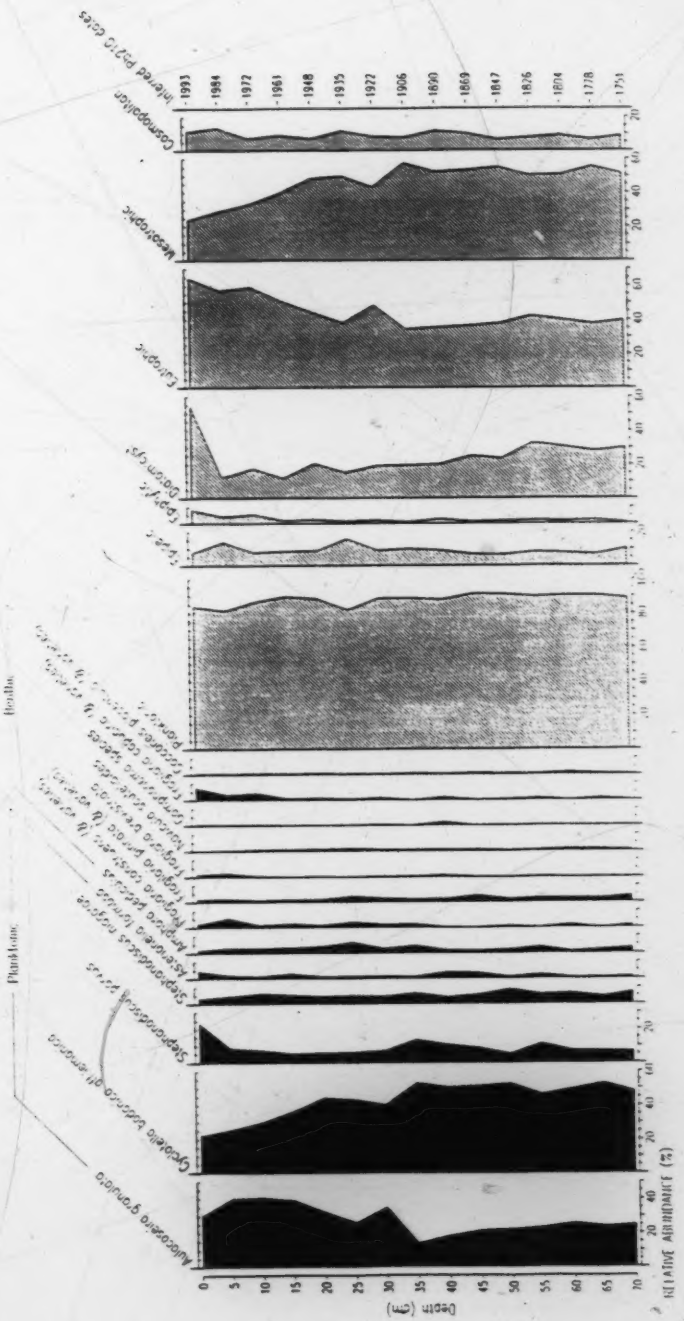

Inferred pollen zones
Cosmopolitan
Mesotrophic
European
Upper C
Quercus cpe
Lower C
Diatoms
Phytoliths
Pediastrum boryanum
Botryococcus braunii
Fragilaria construens
Fragilaria capucina
Fragilaria virescens
Fragilaria brevistriata
Fragilaria pinnata
Asterionella formosa
Staurosirella pinnata
Staurosira construens
Cyclotella bodanica var. comensis
Cyclotella ocellata
Aulacoseira granulata
1993
1984
1972
1961
1948
1935
1922
1906
1890
1869
1847
1826
1814
1778
1753
Depth (cm)
RELATIVE ABUNDANCE (%)

Figure 8: North Core I, Sediment Water, Organic & Carbonate Content
Pine Lake, Alberta, Canada

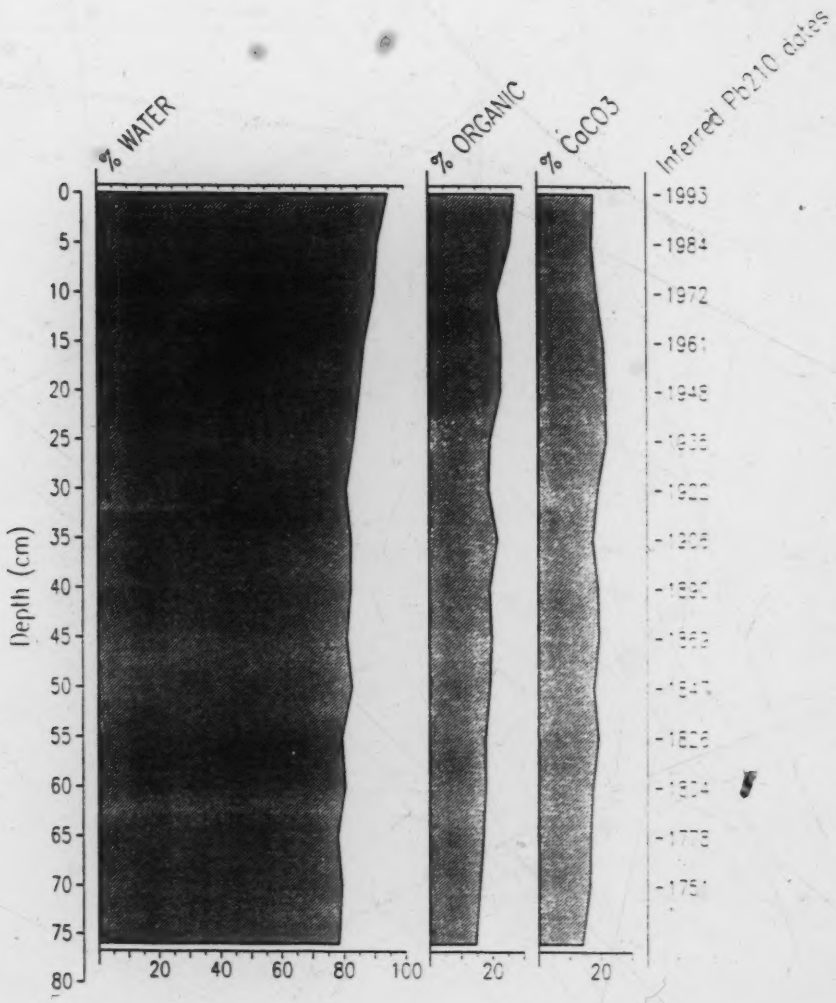
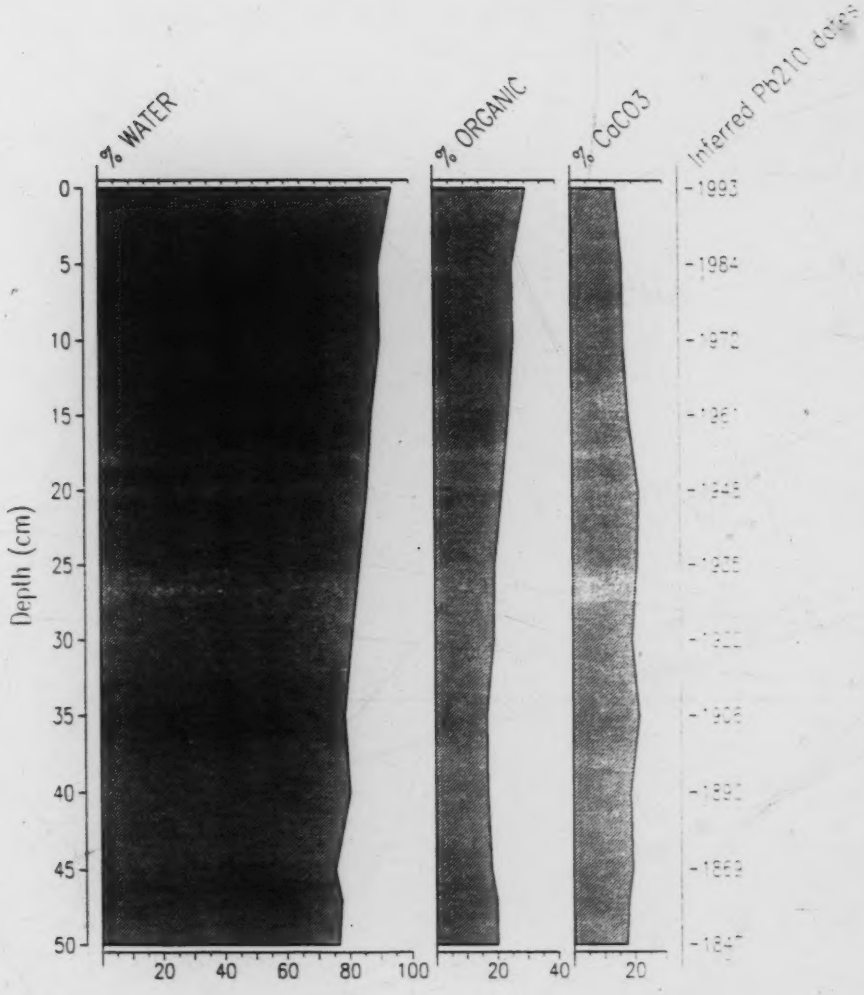

% WATER
% ORGANIC
% CaCO3
Inferred Pb210 dates
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
20
40
60
80
100
20
20
-1993
-1984
-1972
-1961
-1948
-1935
-1922
-1908
-1891
-1868
-1847
-1828
-1804
-1778
-1751

Figure 9: North Core II, Sediment Water, Organic & Carbonate Content
Pine Lake, Alberta, Canada


% WATER
% ORGANIC
% CaCO3
Inferred Pb210 dates
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
20
40
60
80
100
20
40
20
1993
1984
1972
1961
1948
1935
1922
1908
1892
1868
1847

4.3.2 Loss-On-Ignition (% Organic Matter)

Both NCI and NCII gradually increase in percent organic matter with decreasing core depth. NCI ranges from a low value of 12.9% prior to 1751, to a high value of 27.5% ca. 1993. NCII shows a range in percent organic matter from 16.9% at the base, to 30.5% at the top of the core (Figures 8 & 9).

4.3.3 Carbonate Content (%)

Overall, NCI shows a slight increase in carbonate content from 11.4% prior to 1751, to 27.5% ca. 1993. NCII increases slightly ca. 1847 to ca. 1948, at which point it gradually decreases in carbonate content, reaching a minimum value of 14.6% ca. 1993 (Figures 8 & 9).

4.3.4 Diatom Composition

4.3.4.1 North Core I (0-76.0cm)

Cyclotella bodanica aff. *lemanica* dominates from the base of the core (prior to 1751) until ca. 1948 (Figure 10). Within this time frame it has two declines in abundance, one ca. 1751 and one ca. 1869, when *Aulacoseira granulata* has concurrent short-lived dominance. *Aulacoseira granulata* permanently replaces *Cyclotella bodanica* aff. *lemanica* during the past 45 years of the core (Figure 12). *Stephanodiscus parvus* and *Asterionella formosa* are both present in relatively constant abundances throughout the core, increasing during the past 21 years. *Stephanodiscus niagarae* and *Fragilaria brevistriata* are both present at relatively constant abundances throughout the core, with

Fragilaria brevistriata reaching a maximum of 17.0% ca. 1961. *Fragilaria crotonensis* is virtually absent from the core with the exception of one peak ca. 1906 (11.4%).

Mesotrophic diatoms dominate from before ca. 1751 until ca. 1935, at which point they begin to decline, and are replaced by a more eutrophic diatom assemblage towards the top of the core.

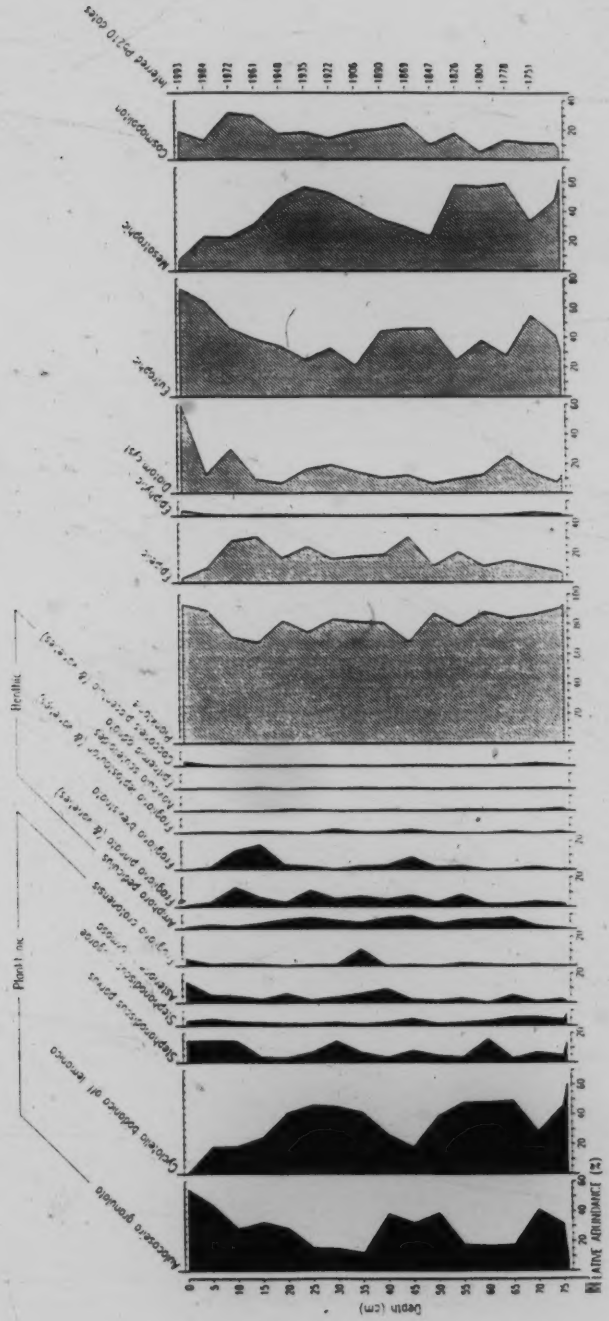
The sediment core is dominated by planktonic diatoms in high abundance (65.0-91.0%). The epipelic population is relatively constant until ca. 1972 after which it starts to decline. The epiphytic component is negligible until the top of the core (ca. 1993) where it comprises 3.5% of the total.

The diatom:cyst ratio is in constant flux until ca. 1984 where it sharply increases to a maximum ca. 1993.

4.3.4.2 North Core II (0-45.0cm)

Aulacoseira granulata dominates the diatom population from ca. 1869 until ca. 1906 and from ca. 1972 to ca. 1993 (Figure 11). It drops in value in the central portion of the core, temporarily being replaced by *Cyclotella bodanica* aff. *lemanica*. *Stephanodiscus parvus* and *Asterionella formosa* are present in small amounts in the core both reaching their maximums in the surface sample. Other important species which are present in low but relatively constant abundances include *Stephanodiscus niagarae* and *Fragilaria construens*, which has a short lived peak ca. 1948 (10.5%). *Fragilaria brevistriata* has its maximum ca. 1961 (13.5%), but otherwise has a negligible presence in the core.

Figure 10: North Core I, Diatom Composition
Pine Lake, Alberta, Canada


Inferred Pb210 dates
1993
1984
1972
1961
1948
1935
1922
1906
1890
1869
1847
1826
1804
1778
1751
Cosmopolitan
Meroplanktic
Estuarine
Oligohaline
Diatom (%)
Epiphytic
Epipsammic
Planktic
Benthic
Fragilaria brevistriata (& varieties)
Fragilaria pinnata (& varieties)
Fragilaria pseudoconstruens
Amphora coffeaeformis
Amphora pediculus
Fragilaria construens
Fragilaria capucina
Asterionella formosa
Stephanodiscus parvus
Stephanodiscus hantzschii
Cyclotella bodanica var. lemanica
Aulacoseira granulata
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
RELATIVE ABUNDANCE (%)

Eutrophic diatoms are the dominant assemblage both at the bottom, and again at the top of the sediment core. They are temporarily replaced by mesotrophic diatoms in the central portion of the core (ca. 1922 to ca. 1948).

The diatom population is primarily planktonic throughout the core. The epipelic and epiphytic populations maintain relatively constant presence, comprising minute percentages throughout most of the core. The epipelic diatoms gradually increase in the central portion of the core, declining again towards the top. The epiphytic population comprises the smallest component of diatoms, and has slightly increased values at the bottom of the core and again at the top. Epiphytes are virtually absent in the central portion of the core.

The diatom:cyst ratio increases gradually towards the top of the core.

4.4 Central Sub-Basin (CCI & CCII)

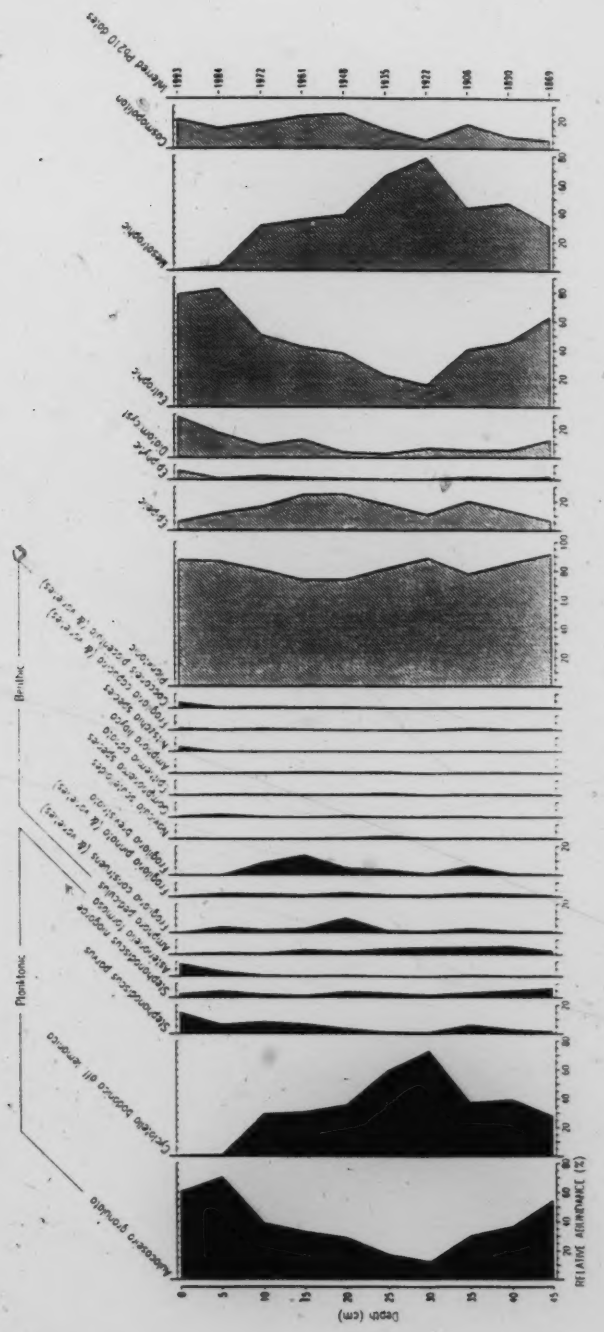
4.4.1 Water Content (%)

Central Core I (0-27.0cm) shows in increase in percent water content from 78.7% ca. 1930 to 92.6% ca. 1993 (Figure 12). Central Core II (0-60.0cm) remains constant except for a slight peak of 82.5% at ca. 1935 (Figure 13).

4.4.2 Loss-On-Ignition (% Organic Matter)

Both CCI and CCII show increases in organic matter towards the top of the core (Figures 12 & 13), with maximum values of 30.4% in CCI and 28.3% in CCII, ca. 1993.

Figure 11: North Core II, Diatom Composition
Pine Lake, Alberta, Canada


Depth (cm)
RELATIVE ABUNDANCE (%)
Planktonic
Benthic
Cosmopolitan
Melosira granulata
Melosira italica
Melosira varians
Aulacoseira granulata
Aulacoseira granulata var. angustissima
Aulacoseira italica
Aulacoseira italica var. tenuissima
Aulacoseira subarctica
Aulacoseira valida
Cyclotella bodanica var. lemanica
Stephanodiscus parvus
Stephanodiscus rotula
Asterionella formosa
Fragilaria crotonensis
Fragilaria pinnata
Fragilaria virescens
Tabellaria flocculosa
Achnanthes minutissima
Achnanthes lanceolata
Cocconeis placentula
Cocconeis placentula var. euglypta
Diploneis elliptica
Epithemia adnata
Epithemia sorex
Epithemia turgida
Gomphonema parvulum
Navicula cryptocephala
Navicula radiosa
Navicula tripunctata
Nitzschia dissipata
Nitzschia fonticola
Nitzschia palea
Nitzschia sigmoidea
Rhoicosphenia abbreviata
Surirella angusta
Surirella ovata
Surirella ovata var. pinnata
Surirella robusta var. splendida
Surirella robusta var. splendida f. recedens
Surirella spiralis
Surirella spiralis var. helvetica
Surirella spiralis var. kuetzingii
Surirella tenera
Surirella tenera var. nervosa
Unidentified
Indeterminate
Reflected Pb210 dates

4.4.3 Carbonate Content (%)

In CCI percent carbonates shows a slight decline from 21.1% ca. 1930 to 15.45% ca. 1993 (Figure 12). Carbonate levels remain relatively constant throughout CCII with the exception of a slight peak of 36.2% ca. 1948 (Figure 13).

4.4.4 Diatom Composition

4.4.4.1 Central Core I (0-27.0cm)

Cyclotella bodanica aff. *lemanica* dominates the diatom population until ca. 1948, where it is replaced by *Aulacoseira granulata* in the top of the core (Figure 14). *Stephanodiscus parvus* and *Stephanodiscus niagarae* are both present in minor amounts throughout the core, having their maxima in the past 21 years. However, *Fragilaria pinnata*, *Fragilaria brevistriata*, and *Amphora pediculus* reach their maxima in the central portion of the core (ca. 1930 to ca. 1984), with minimal abundances in the top portion of the core. *Fragilaria capucina* and *Cocconeis placentula* are both absent in the bottom portions of the cores, reaching their maximum abundances from ca. 1972 until present.

The mesotrophic population dominates the core from ca. 1930 to ca. 1972, where it rapidly declines and is increasingly replaced by eutrophic diatom species. Cosmopolitan diatoms are present throughout the core, peaking at ca. 1961.

Planktonic diatoms dominate the core throughout (62.0-80.0%). Epipelic diatoms, also present throughout the core, reach a maximum ca. 1961 (43.0%) where they then decline with decreasing depth. Epiphytic diatoms have a smaller presence, increasing in abundance in the top 21 years of the core (6.0-11.0%).

Figure 12: Central Core I, Sediment Water, Organic & Carbonate Content
Pine Lake, Alberta, Canada

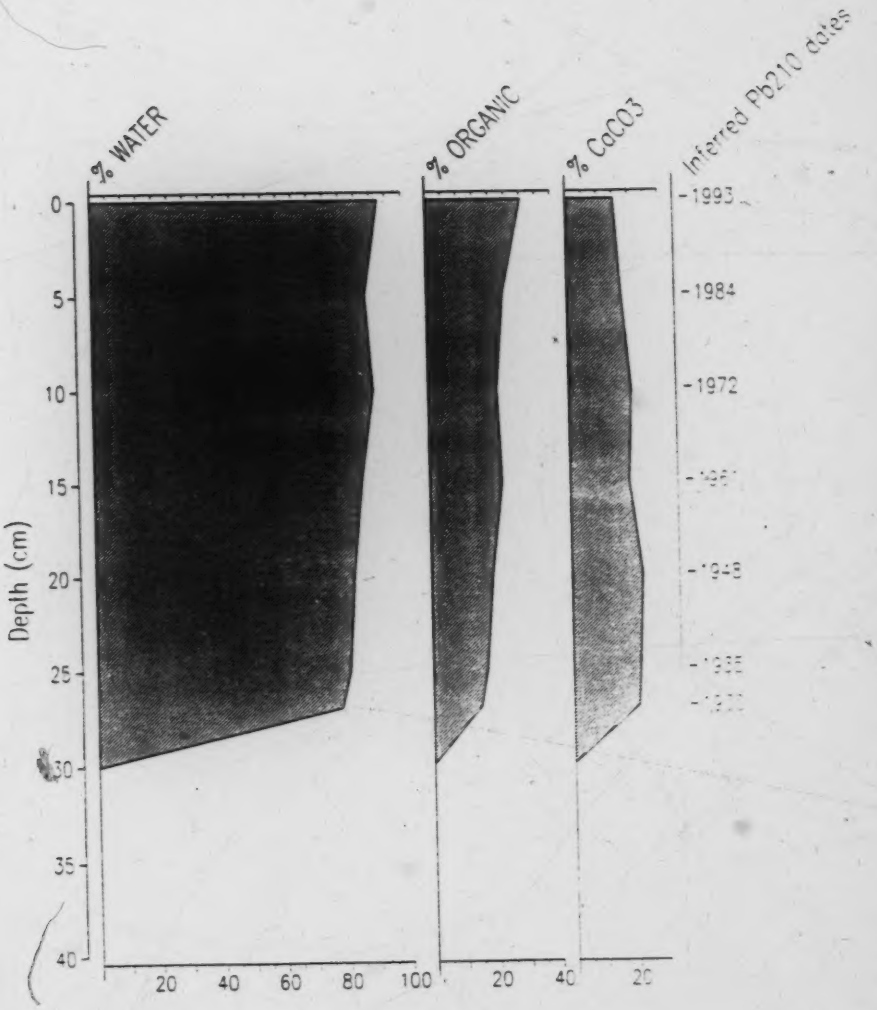

% WATER
% ORGANIC
% CaCO3
Inferred Pb210 dates
Depth (cm)
0
5
10
15
20
25
30
35
40
20
40
60
80
100
20
40
20
1993
1984
1972
1948

Figure 13: Central Core II, Sediment Water, Organic & Carbonate Content
Pine Lake, Alberta, Canada

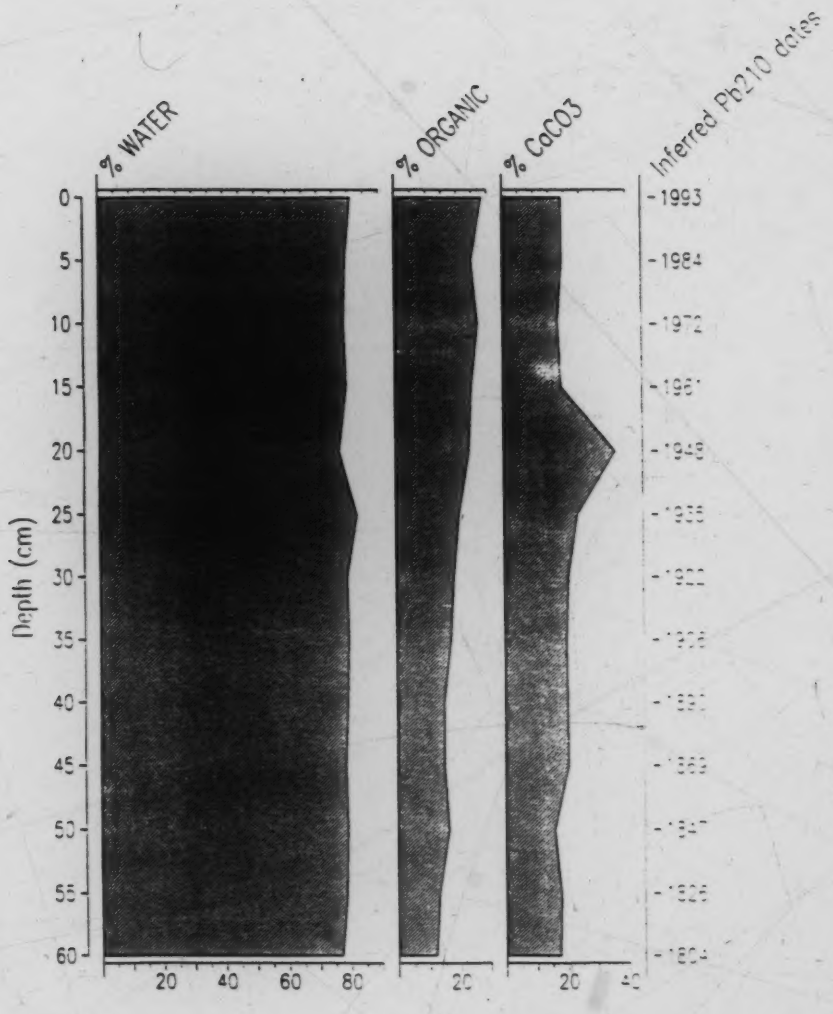
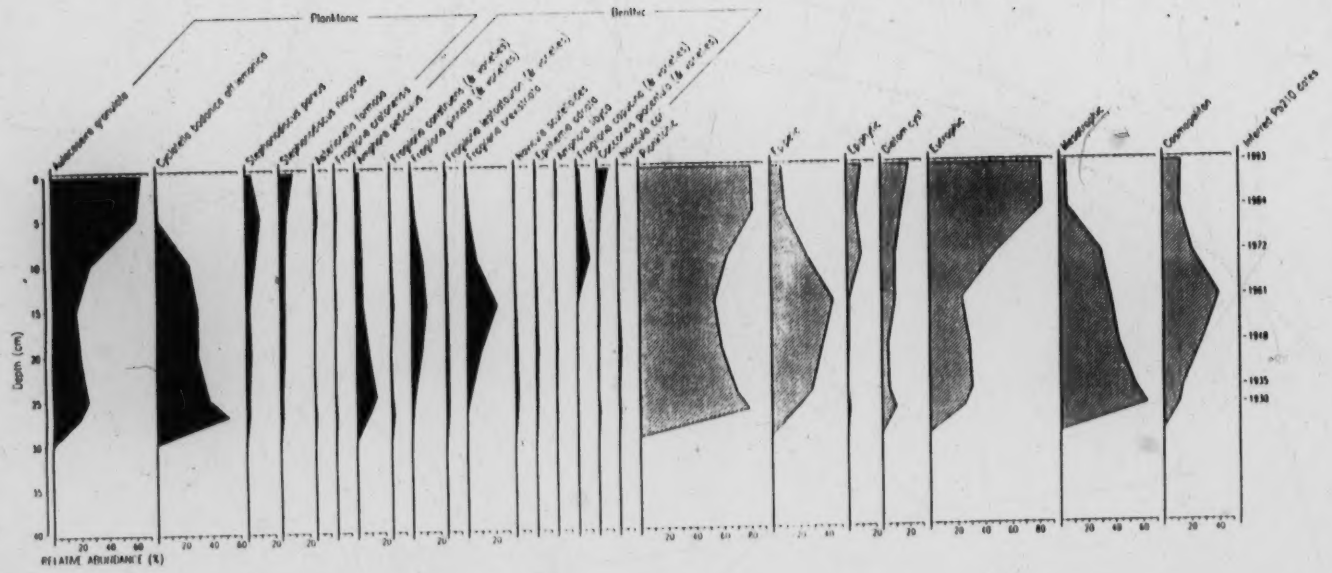

% WATER
% ORGANIC
% CaCO3
Inferred Pb210 dates
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
20
40
60
80
20
20
1993
1984
1972
1961
1949
1938
1922
1908
1891
1869
1847
1826
1804

Figure 14: Central Core I, Diatom Composition
Pine Lake, Alberta, Canada


Planktonic
Benthic
Aulacoseira granulata
Cyclotella bodanica var. ambigua
Stephanodiscus parvus
Stephanodiscus neoastraea
Asterionella formosa
Fragilaria crotonensis
Diatoma elongatum
Fragilaria capucina (b varieties)
Fragilaria pinnata (b varieties)
Fragilaria construens (b varieties)
Fragilaria virescens
Navicula radiosa
Epithemia adnata
Amphora ovalis
Fragilaria brevistriata (b varieties)
Cocconeis placentula (b varieties)
Navicula cryptocephala
Tabellaria
Tabellaria flocculosa
Cyclotella
Cocconeis placentula
Eunotia
Melosira varians
Concentration
Inferred Pb210 dates
Depth (cm)
RELATIVE ABUNDANCE (%)
1993
1984
1972
1961
1948
1935
1930

The diatom:cyst ratio increases gradually towards the top of the core, reaching a maximum ratio of 540 valves: 26 cysts ca. 1993.

4.4.4.2 Central Core II (0-60.0cm)

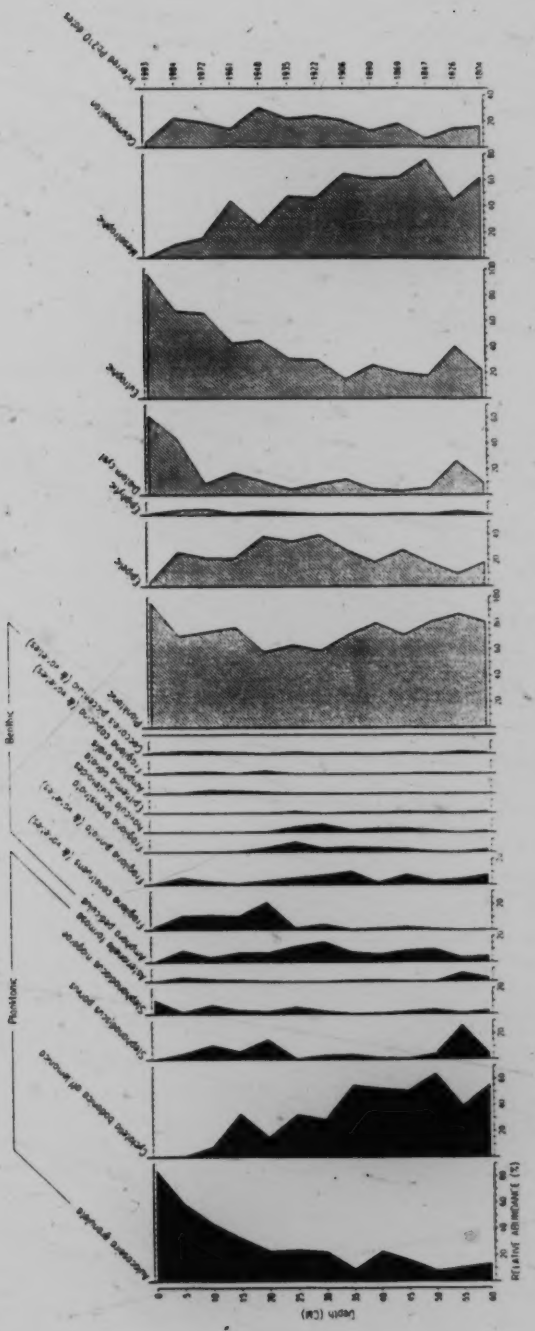
Cyclotella bodanica aff. lemanica is the dominant species in the basal portion of the core, being replaced by *Aulacoseira granulata* during the past 58 years of the core (Figure 15). Other important diatom species include *Stephanodiscus parvus* and *Asterionella formosa*, which both have their maximums in the bottom portion of the core, *S. parvus* at ca. 1847 and *A. formosa* at ca. 1826. *Fragilaria construens* (& varieties) and *Stephanodiscus niagarae* have their maximums ca. 1948. *Amphora pediculus* reaches its greatest abundance in the central portion of the core (ca. 1847 to ca. 1948), and declines towards the top of the core along with *Fragilaria construens*.

The mesotrophic diatom population dominates until ca. 1922 where it declines and is replaced by eutrophic diatom species towards the top of the core. Cosmopolitan diatom species are present throughout the core in consistent abundances.

Planktonic diatoms dominate the core, with epipelic and epiphytic diatoms making up considerably smaller proportions of the diatom assemblage. Epipelic diatoms reach their greatest abundance in the central region of the core (ca. 1869 to ca. 1984), and decline towards the top. Epiphytic diatoms contribute minimally to the overall population. They have their greatest abundance at the bottom of the core until ca. 1847 (2.0%), and then again at the top of the core from ca. 1935 to ca. 1993 (5.0%).

The diatom:cyst ratio shows an early peak ca. 1826. It then declines until ca. 1948

Figure 15: Central Core II, Diatom Composition
Pine Lake, Alberta, Canada


Depth (cm)
RELATIVE ABUNDANCE (%)
Planktonic
Benthic
Aulacoseira granulata
Cyclotella bodanica var. lemanica
Stephanodiscus parvus
Stephanodiscus neoastraea
Asterionella formosa
Fragilaria crotonensis
Fragilaria pinnata
Fragilaria capucina
Fragilaria ulna
Achnanthes minutissima
Navicula spp.
Cocconeis placentula
Fragilaria spp.
Diatoms (#)
Chrysophyta
Cryptophyta
Chlorophyta
Pyrrophyta
Cyanophyta
Diatom Accum. Rate (# cm-2 yr-1)

where it increases reaching maximum values in the surface sediments.

4.5 Pigment Concentrations

4.5.1 Central Core II (0-60.0cm)

Chlorophyll *c* is absent below ca. 1890. It slowly starts to increase reaching its maximum of 15,120.0 nmoles/L at ca. 1993 (Figure 16).

In the first half of the core, from ca. 1804 to ca. 1948, fucoxanthin is found in negligible amounts. It reaches its maximum of 16,396.0 nmoles/L at ca. 1993.

Phaeophorbide *a* slowly increases from 0.0 nmoles/L at ca. 1804 to a maximum concentration of 15,359.0 nmoles/L at ca. 1972. It declines from this point to 1,216.5 nmoles/L at the top of the core (ca. 1993).

Myxoxanthophyll maintains approximately the same concentration from ca. 1804 to ca. 1972, with peaks at ca. 1826 and ca. 1906. At ca. 1972 it increases drastically, reaching a maximum value of 7,926.0 nmoles/L in the surface sample (ca. 1993).

Diatoxanthin displays a slight increase in concentration from ca. 1804 to ca. 1993. It reaches its maximum (44,291.0 nmoles/L) at ca. 1948 to ca. 1935.

Lutein-Zeaxanthin remains fairly constant from ca. 1804 to ca. 1922. After ca. 1922 the pigment concentration starts to increase, reaching a maximum of 68,584.0 nmoles/L at ca. 1948. It declines from there to a minimum value of 18,941.0 nmoles/L at ca. 1961, and then increases towards the top of the core (ca. 1993).

Chlorophyll *b* remains at a fairly constant concentration from ca. 1804 to ca. 1993, exhibiting peak increases and declines. At ca. 1972 there is a sharp decline in pigment

concentration to 34,618 nmoles/L. The maximum pigment concentration is 134,360.0 nmoles/L at ca. 1826.

Chlorophyll *a* shows a slight increase in concentration towards the top of the core. The peak maximum of 77,490.0 nmoles/L occurs ca. 1826, and the peak minimum of 3,887.0 nmoles/L at ca. 1948.

Phaeophytin *b* exhibits a gradual decline in concentration from ca. 1804 to ca. 1993. It reaches a maximum concentration of 18,677.0 nmoles/L at ca. 1826, and a minimum of 1,076.0 nmoles/L at ca. 1948.

Beta-carotene has its maximum concentration of 26,355.0 nmoles/L at ca. 1826 and a minimum concentration of 4,422.0 nmoles/L at ca. 1984, displaying a decreasing trend in pigment concentration from the bottom of the core to the top of the core.

Pyrophaeophorbide *a* shows an overall slight, but steady decline in concentration from ca. 1804 to the surface sample (ca. 1993).

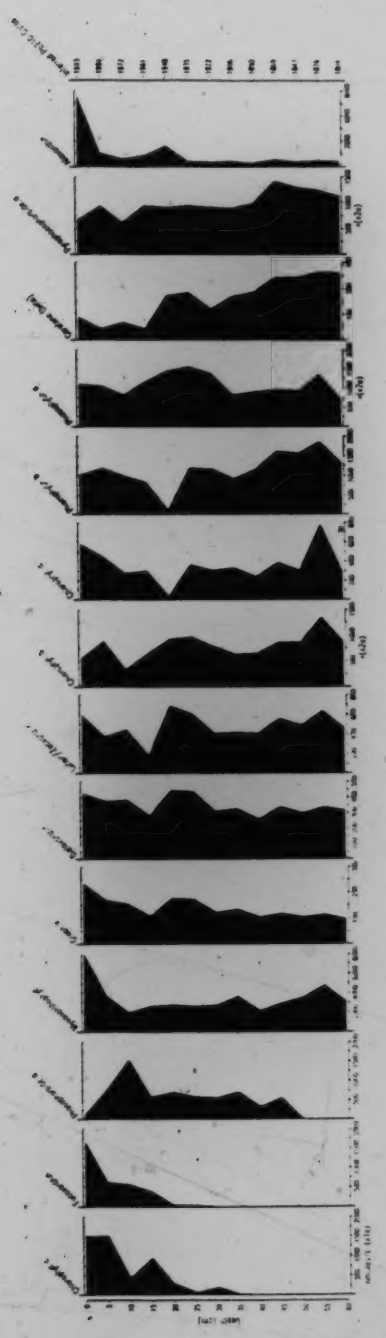
Alloxanthin remains at fairly low concentrations from ca. 1804 to ca. 1972 with one minor peak increase ca. 1948. At ca. 1984 it increases abruptly reaching a maximum concentration of 5,455.1 nmoles/L at ca. 1993.

Phaeophytin *a* remains at a constant concentration from the bottom of the core towards the top. Pigment concentrations are at a maximum of 155,140.0 nmoles/L from ca. 1922 to ca. 1948.

4.6 Core Correlation

The cores were correlated using the Mann-Whitney Test and the Kendall

Figure 16: Central Core II, Pigment Composition
Pine Lake, Alberta, Canada



Coefficient of Concordance. Statistical calculations and results are presented within Appendices II and III.

4.6.1 Mann-Whitney Test

This test was used to compare within sub-basin cores to test similarity based on the diatom data. Seven diatom species were used, and were ranked from highest to lowest in percent abundance among the replicate cores (Appendix II). The test was applied to the central cores (CCI & CCII), the south cores (SCI & SCII, SCII & SCIII), and the north cores (NCI & NCII). The Mann-Whitney test is a two-tailed test, therefore, U and U' are both calculated and the larger value of the pair is the value that is compared against a critical value ($U_{\alpha(2),n2,n1)}$; Appendix II). If either U or U' is equal to or greater than the critical value, the null hypothesis (H_0) is rejected at that level of significance (Appendix II provides formulae and sample calculation). For all three sub-basins, the null hypothesis was identical except for the cores being tested at any given time. The null hypothesis was that Core x and Core y had similar diatom counts. In all instances, the null hypothesis was accepted at 0.05 level of significance (Tables 4,5,6).

4.6.2 Kendall Coefficient of Concordance

This test was used to correlate between-site cores simultaneously. The same 7 diatom species used in the Mann-Whitney Test were used in calculating the Kendall Coefficient. In this case, the diatom counts were ranked within a core and the data compiled into tabular form (Appendix III). A coefficient (W) is calculated. This value is

then tested for significance using the $s_{observed}$ and comparing it to a critical value (Appendix III). When the $s_{observed}$ is greater than the $s_{critical}$ the null hypothesis (H_o) is rejected at a certain level of significance, either 0.05 or 0.01. The null hypothesis, in all calculations, is that the core species compositions are unrelated. The coefficient was calculated in 3 instances. First, using the south cores (SCI, SCII, SCIII), and assuming that their depth intervals are equivalent. Second, all of the cores except South Core II were used to calculate W, and finally, Central Core I was excluded due to its short length.

At all depth intervals, and all coefficients calculated, the null hypothesis was rejected at the 0.05 level of significance. In most cases, the null hypothesis was rejected at the 0.01 level of significance as well (Tables 7,8,9).

Pine Lake core data was first assessed within each of the three sub-basins to determine whether there were significant differences between cores taken from a single site. The two-tailed Mann-Whitney Test was used for this purpose. In all cases (North, South, & Central sub-basins) the null hypothesis that there are no significant differences between vertical profiles based on diatom data was accepted (Tables 4,5,6).

The Kendall Coefficient of Concordance was used to determine if any significant differences existed between the three sub-basins. All cores were simultaneously tested and in all cases the null hypothesis, which stated that the cores were unrelated, was rejected (Tables 7,8,9).

The diatom species utilised in the statistical tests were found to be similar both within a site, and between the three sites within Pine Lake. Based on these results the Pb^{210} dates from South Core III were inferred for the other six lake cores (Table 3).

Table 4. Mann-Whitney Test Results for the South Cores (SCI & SCII)

Depth (cm)	U	U'	Critical Value	H_o/H_A
0	**19**	11	27	19<27 Accept H_o
5	**31**	18	41	31<41 Accept H_o
10	**26**	23	41	26<41 Accept H_o
15	22	**27**	36	27<36 Accept H_o
20	**23**	13	31	23<31 Accept H_o
25	**27**	15	41	27<41 Accept H_o
30	**34**	15	41	34<41 Accept H_o
35	16	**20**	31	20<31 Accept H_o
40	**24**	18	36	24<36 Accept H_o
45	**23**	19	36	23<36 Accept H_o
50	15	**27**	36	27<36 Accept H_o
55	**27**	15	36	27<36 Accept H_o
60	20	**22**	36	22<36 Accept H_o
65	**26**	23	41	26<41 Accept H_o

Table 5. Mann-Whitney Test Results for the North Cores (NCI & NCII)

Depth (cm)	U	U'	Critical Value	H_o/H_A
0	**22**	20	31	22<31 Accept H_o
5	**27**	22	41	27<41 Accept H_o
10	**24**	18	36	24<36 Accept H_o
15	**23**	19	36	23<36 Accept H_o
20	19	**23**	31	23<31 Accept H_o
25	**27**	15	36	27<36 Accept H_o
30	**25**	11	31	25<31 Accept H_o
35	**26**	16	36	26<36 Accept H_o
40	**25**	24	41	25<41 Accept H_o
45	**30**	19	41	30<41 Accept H_o

Table 6. Mann-Whitney Test Results for the Central Cores (CCI & CCII)

Depth (cm)	U	U'	Critical Value	H_o/H_A
0	**21**	3	22	21<22 Accept H_o
5	9	**26**	30	26<30 Accept H_o
10	14	**22**	31	22<31 Accept H_o
15	11	**31**	36	31<36 Accept H_o
20	15	**21**	31	21<31 Accept H_o
25	15	**20**	30	20<30 Accept H_o

Table 7. Kendall Coefficient of Concordance Results:
South Cores (SCI, SCII, SCIII)
At 0.05 level of significance the $s_{critical} = 157.3$ $W_{critical} = .624$
At 0.01 level of significance the $s_{critical} = 185.6$ $W_{critical} = .737$

N = 7, k = 3

Depth (cm)	$s_{observed}$	$W_{observed}$	Outcome of H_o
0/1*	196	0.78	Reject
5	174	0.69	Reject**
10	232	0.92	Reject
15	236	0.94	Reject
20	240	0.95	Reject
25	232	0.92	Reject
30	221.5	0.88	Reject
35	166.5	0.66	Reject**
40	210	0.83	Reject
45	214	0.85	Reject
50	218	0.87	Reject
55	236	0.94	Reject
60	232.5	0.93	Reject
65	200.9	0.8	Reject

*South Core III starts at 1cm.
**The null hypothesis could only be rejected at the 0.05 level of significance not at the 0.01 level of significance.

Table 8. Kendall Coefficient of Concordance Results:
CCI, CCII, NCI, NCII, SCI, SCIII
At a level of significance of 0.05, $s_{critical} = 335.2$ $W_{critical} = .333$
At a level of significance of 0.01, $s_{critical} = 422.6$ $W_{critical} = .419$

N = 7, k = 6

Depth (cm)	$s_{observed}$	$W_{observed}$	Outcome of H_o
0/1*	652.43	0.66	Reject
5	610	0.61	Reject
10	794	0.79	Reject
15	814	0.81	Reject
20	682.5	0.68	Reject
25	918	0.91	Reject

*South Core III starts at 1.0cm.

Table 9. Kendall Coefficient of Concordance Results:
CCII, NCI, NCII, SCI, SCII, SCIII
∝Level of significance.

Depth (cm)	k	N	$W_{observed}$	$W_{critical}$ 0.05∝	$W_{critical}$ 0.01∝	Outcome H_o
0/1*	6	7	0.69	0.333	0.419	Reject
5	6	7	0.6	0.333	0.419	Reject
10	6	7	0.78	0.333	0.419	Reject
15	6	7	0.8	0.333	0.419	Reject
20	6	7	0.68	0.333	0.419	Reject
25	6	7	0.89	0.333	0.419	Reject
30	6	7	0.81	0.333	0.419	Reject
35	6	7	0.85	0.333	0.419	Reject
40	6	7	0.74	0.333	0.419	Reject
45	6	7	0.84	0.333	0.419	Reject
50	5	7	0.82	0.395	0.491	Reject
55	5	7	0.84	0.395	0.4918	Reject
60	5	7	0.9	0.395	0.491	Reject
65	4	7	0.76	0.484	0.592	Reject
70	3	7	0.88	0.624	0.737	Reject

*South Core III starts at 1.0cm.

5. DISCUSSION

5.1 Core Correlation & Chronology

Assessments of spatial variability and heterogeneity in diatom stratigraphy usually involves core correlation in order to assess core similarities and/or differences (Anderson et al., 1994). Core correlation involves the biostratigraphic matching of cores and the utilization of sequence slotting (Anderson, 1986) and ordination techniques (Birks, 1987), to improve accuracy. Biostratigraphic correlation has been found to be more reliable when compared to numerical sequence slotting (Birks, 1979), which can cause abnormal results by force fitting the profiles to correlate (Anderson, 1986). When several cores in a lake all show the same response to eutrophication, biostratigraphic correlation has been found to be quite applicable (Anderson, 1986). The Pine Lake core profiles all displayed similar trends in response to anthropogenic effects. Biostratigraphic correlation was therefore used, and non-parametric statistics were utilised to improve accuracy and to aid in core chronology.

Non-parametric statistics or distribution-free tests, do not make any assumptions about the sample population distribution, they do not require population variance or mean estimation, and the hypotheses do not state any parameters (Seigel, 1988). As a group of statistical methods, non-parametric statistics possess a number of advantages compared to their parametric counter-parts (Kreis, 1986). Non-parametric statistical tests are quicker and easier to apply and the collected data is less subject to the stringent assumptions found in parametric statistical tests (Seigel, 1988).

Pine Lake core data was first assessed within each of the three sub-basins to

determine whether there were significant differences between cores taken from the a single site. The two-tailed Mann-Whitney Test (Mann & Whitney, 1947) was used for this purpose. In all cases (north, south & central sub-basins) the null hypothesis that there are no significant differences between vertical profiles based on diatom data was accepted (Tables 4,5,6).

The Kendall Coefficient of Concordance (Friedman, 1940) was used to determine if any significant differences between the three sub-basins existed. All cores were simultaneously tested and in all cases the null hypothesis, which stated that the cores were unrelated, was rejected (Tables 7,8,9).

The diatom species utilised in the statistical tests were found to be similar both within a site and between the three sites. This agrees with Watson (1993) who found that the relative proportions of taxa among the North, Central, and South sampling stations were similar. Differences in the phytoplankton biomass between the three stations were attributed to physical factors (water movement, wind) rather than to within-lake spatial changes (Watson, 1993).

Based on these results, the Pb^{210} dates from South Core III were inferred for the other six lake cores in the Pine Lake basin (Hickman & Schweger, 1996; Campbell 1996).

5.2 Loss-On-Ignition, Carbonate Content, & Water Content Analysis

Loss-on-ignition and carbonate content are fairly constant throughout the Pine Lake basin. The loss-on-ignition in the three sub-basins shows a gradual increase over time, showing maximum percent abundance in the top 5cm of the cores (ca. 1984-1993).

An increase in organic matter could be associated with an increase in phytoplankton (non-siliceous) input (Anderson, 1989). The carbonate content decreases slightly over time leading to minimum percentages ca. 1993. Central Core II exhibits a slightly different trend with an abrupt and short-lived peak in carbonate content in ca. 1948. A similar occurrence at Wood Lake in the Okanagan Valley happened in ca. 1940 and was attributed to intensified use of pesticides and chemical fertilizer in theOkanagan Valley at this time (Walker et al., 1993).

5.3 Diatom Analysis: South Sub-Basin

The diatom composition in the south sub-basin shows an increase over time in species characteristic of eutrophic conditions. Overall, *Aulacoseira granulata* displays an increase in percent abundance towards the present day. *Aulacoseira granulata* is an indicator of eutrophic conditions (Bradbury & Waddington, 1973). It is abundant in lake waters containing high concentrations of nutrients and which receive large quantities of anthropogenic input, resulting in culturally induced eutrophication (Stoermer et al., 1981). In both South Core I and II there is a drop in *A.granulata* abundance which is replaced by an increase in *Cyclotella bodanica aff. lemanica* around ca. 1926 and lasting until ca. 1953, where the roles are again reversed and *A. granulata* becomes the dominant. This drop in *A. granulata* may be related to a decrease in agriculture during the depression era, allowing Pine Lake to revert to more mesotrophic conditions. *C. bodanica aff. lemanica* is more commonly found in circumneutral oligotrophic-mesotrophic waters (Kling & Håkansson, 1988). Previous investigations have noted that it disappears as a lake system

becomes more eutrophic (Klee & Schmidt, 1987). In South Core I and II, *C. bodanica aff. lemanica* has all but disappeared in the core profile around ca. 1991. In South Core III, it is on the decline at this same time. The two diatom profiles of *A. granulata* and *C. bodanica aff. lemanica* seem to exhibit inversely proportional relationships throughout the cores.

Stephanodiscus parvus exhibited a fairly consistent presence throughout the three south core profiles. *S. parvus* increases in abundance around ca. 1978 in South core I and slightly later in South Core III. This species is considered to be a eutrophic indicator (Anderson et al., 1990; Christie & Smol, 1993). The increase in the presence of *S. parvus* in the uppermost portion of the cores is suggestive of an increase in eutrophic conditions in Pine Lake. *Stephanodiscus niagarae* is also present in fairly steady percent abundances throughout the cores. *S. niagarae* is typical of eutrophic systems and has been found in lakes with low transparency levels and high sulphate levels (Håkansson & Régnell, 1993). It is commonly found in association with *A. granulata* (Håkansson & Régnell, 1993). In South Core II, *S. niagarae* has a peak initiated in ca. 1940, possibly suggestive of increased human activity (campground initiation) around the lake causing an increase in turbulence and perhaps nutrient cycling which is a favorable condition for *S. niagarae*.

In South Core I, *Asterionella formosa* increases to a maximum around ca. 1983 and remains at high levels until present day. Prior to this, *A. formosa* was present in the core in low frequencies. *A. formosa* has a wide distribution and adapts readily to changes in water chemistry and nutrient levels (Anderson et al. 1993; Bradbury & Waddington 1973). An increase in *A. formosa* has been shown to be associated with anthropogenic

nutrient loading (Brugam & Vallarino 1989; Anderson 1994) and is often paired with a simultaneous rise in *Fragilaria crotonensis* due to human settlement in the catchment (Brugam & Patterson 1983; Stockner 1978).

In all of the south cores, *Fragilara capucina* shows an increase around ca. 1991. *Fragilaria capucina* is characteristic of alkaline, naturally occurring mesotrophic-eutrophic conditions (Bradbury & Waddington, 1973) and with areas that receive heavy nutrient loads such as the Great Lake Region (Stoermer et al., 1985). Its presence suggests more complete water circulation at times, particularly during the spring. *F. capucina* is a diatom species that lives both epiphytically and planktonically, although it is considered primarily to be a benthic species, indicative of a well developed epiphytic community. In the spring, it forms large epiphytic populations upon both emergent and submergent macrophytes (Klarer & Hickman, 1975; Hickman 1982), and is incorporated into the plankton after detachment in the summer. Submergent and emergent macrophytes comprise 14.8% of the lake surface area and shoreline of Pine Lake (Sosiak & Trew, 1996), providing a large area of host plants for epiphytic diatoms, such as *F. capucina*.

5.4 Diatom Analysis: North Sub-Basin

Aulacoseira granulata and *Cyclotella bodanica aff. lemanica* are again the dominant species in the two north cores, exhibiting an inversely proportional relationship with one another. *A. granulata* is the dominant at the base of North Core I occurring around ca. 1745 until just prior to ca. 1801. Since North Core II is shorter, the initial dominance of *A. granulata* over *C. bodanica aff. lemanica* is not visible. After ca. 1801,

A. granulata declines and *C. bodanica aff. lemanica* takes over, indicating that less eutrophic conditions prevailed until prior to ca. 1888 where *A. granulata* regains dominance. Around ca. 1973, *A. granulata* starts to increase, reaching maximum abundance in the top of the core (present day). *C. bodanica aff. lemanica* begins to drop off in abundance around ca. 1986 in North Core II, and later in North Core I disappearing completely after ca. 1991.

Stephanodiscus parvus and *Stephanodiscus niagarae* both maintain a constant presence in the two north cores. The higher percent abundances observed for *S. niagarae* are coincident with increases in *A. granulata*. The paired presence of these two species may be related to an increase in sulphate levels and a decrease in the transparency of the water (Håkansson & Regnéll, 1993). *Stephanodiscus parvus* shows an increase towards the top of both North Core I and North Core II. Its presence remains low in NCII until ca. 1948 at which point it begins to increase, reaching its maximum ca. 1993. This differs from the NCI profile, where *S. parvus* exhibits two early peaks, the first at ca. 1804 and the second at ca. 1922. Both peaks correspond with a resurgent dominance of *Cyclotella bodanica aff. lemanica*. It has been observed that *S. parvus* often blooms prior to the late spring development of herbivores (Bradbury, 1975). Seasonality may be responsible for the coincident peaks if the two species share the same blooming periods. However, the increase of *S. parvus* seen in the top portion of the core, concurrent with an increase in *A. granulata* indicates an increase in eutrophic conditions (Christie& Smol, 1993).

Asterionella formosa shows an increase in abundance in both cores ca. 1993. Prior to ca. 1972 it was virtually nonexistent in North Core II, whereas in North Core I, it

exhibited several fluctuations in abundance, reaching a near maximum peak occurring prior to a *Fragilaria crotonensis* peak maximum at ca. 1906. *A. formosa* has wide environmental tolerances allowing it to flourish in a wide range of nutrient concentrations (Anderson et al. 1993). It has also been noted that there is a strong relationship between a rise in *A. formosa* and human disturbance (Brugam & Vallarino, 1989). An abundance of *A. formosa* in association with *F. crotonensis* may be indicative of a rise in human settlement, leading to an increase in land erosion and nutrient influx (Stockner, 1978). Culture experiments on *A. formosa* have shown that it can grow efficiently when high Si:P conditions prevail (Engstrom et al., 1991). It has also been shown that *F. crotonensis* is a successful competitor for phosphorous, so when high Si:P ratios exist, this species can still prosper (Dean et al. 1994).

5.5 Diatom Analysis: Central Sub-Basin

Aulacoseira granulata and *Cyclotella bodanica aff. lemanica* are the main diatom species in both central sub-basin cores. *A. granulata* is present in low percent abundances in both cores until ca. 1972, whereupon it increases and reaches its maximum at ca. 1993. Conversely, *C. bodanica aff. lemanica* was dominant in fluctuating abundances until ca. 1972, quickly becoming a minor part of the biota as *A. granulata* increased. Due to the shortness of Central Core I (CCI) this is not observed. It would seem that Pine Lake was mesotrophic until 1972 at which point it became increasingly more eutrophic. Increased abundances of *A. granulata* is often associated with areas where nutrients are abundant (Owen & Crossley, 1992) and has been related to anthropogenic input (Stoermer et al.

1981). As eutrophication progresses it has been observed that *C. bodanica aff. lemanica* completely disappears (Klee & Schmidt, 1987).

Stephanodiscus niagarae, a characteristic species of eutrophic bodies of water (Engstrom et al., 1985), is present in both CCI and CCII, increasing slightly towards ca. 1993. *Stephanodiscus parvus* in CCI is present in greater quantities from ca. 1961 until present. In CCII, *S. parvus* has a stronger presence in two areas of the core. The earliest peak occurs at ca. 1826 and corresponds with a decline in *C. bodanica aff. lemanica.* This may be indicative of a catchment event during which nutrient flow into the lake increased for a brief period of time resulting in an increase in a eutrophic species such as *S. parvus* (Håkansson & Regnéll, 1993). The second peak of *S. parvus* occurs between ca. 1948 and ca. 1972 after which it gradually declines to near zero values around ca. 1993. This decline in *S. parvus* may be indicative of a high silica to phosphorous ratio, a condition in which *S. parvus* does not grow well (Engstrom et al., 1991) but in which *A. granulata* thrives (Owen & Crossley, 1992).

Amphora pediculus has a strong presence in the central sub-basin. *A. pediculus* is an epipelic species found living upon submerged sediments (Hickman & Schweger, 1996). In CCI, it is present throughout the entire core, with a peak at ca. 1935. In CCII, it is also present throughout, with its greatest presence occurring ca. 1922. Since *A. pediculus* is an epipelic species, where it is found in great percentages could be indicative of greater water transparency levels

Fragilaria construens (including all varieties), although virtually absent in CCI, has a greater percent abundance than *S. parvus* from ca. 1948 until ca. 1993. It has been

found that *F. construens*, along with other *Fragilaria* species, may be respresentative of eutrophic conditions in shallow bodies of water (Hickman et al., 1984).

5.6 The Diatom Community Types

Throughout Pine Lake, the planktonic community remains dominant which indicating higher nutrient levels (Engstrom et al., 1991). Pine Lake is also generally characterized by a few dominant diatom species which is typical of productive lakes (Bradbury & Waddington, 1973). An increase in epiphytic diatoms or aquatic macrophytes may result from a variety of factors associated with the increase in runoff that logically follows forest clearance (Håkansson & Regnéll, 1993). In all three of the Pine Lake sub-basins, there is an increase in the epiphytic community towards the top of all sediment cores. There is also an overall decline in the epipelic community, which could be indicative of decreasing light penetration in Pine Lake (Hickman & Schweger, 1991).

5.7 The Diatom:Chrysophyte Ratio

The diatom:chrysophyte ratio in all six sediment cores, across the three sub-basins, increased towards a present day maximum (ca. 1993). The increases varied in initiation between the six sediment cores from as early as ca. 1948 to as late as ca. 1984. Chrysophyte cysts are often used as indicators of oligotrophic conditions (Smol, 1985). Their decrease in relative concentrations towards present day in Pine Lake is indicative of eutrophication. In many cases an inverse relationship exists between chrysophyte abundance and phosphorous concentration in a lake (Nicholls, 1976). A lake with high

productivity may also prevent high abundances of chrysophytes from occurring (Sandgren, 1988).

5.8 Pigment Analysis: Central Core II

Myxoxanthophyll, a pigment which represents colonial and filamentous cyanobacteria, maintains a steady presence in CCII from ca. 1804 until ca. 1972. After ca. 1972, it abruptly increases towards the top of the core, indicating either a better preservation of cyanobacterial pigments through sedimentary anoxia (Engstrom et al., 1985), or an actual increase in cyanobacterial production which is often associated with eutrophication (Gorham et al. 1974).

Chlorophyll *c* (Chrysophyta, Dinophyta) and Fucoxanthin (Chrysophyta, Bacillariophyta) are both absent in the earlier portion of CCII, from ca. 1804 until ca. 1906 for Chlorophyll *c* and later at ca. 1948 for Fucoxanthin. After their initial appearance, both pigments show a quick increase towards the top of the core ca. 1993. Sediment trap and short core comparisons show that diatom pigments (diadinoxanthin, fucoxanthin, chlorophyll *c*) and phaeophorbide *a* degrade faster than other pigments (Hurley & Armstrong, 1991). If this were true for Pine Lake, phaeophorbide *a* should be absent in the first half of the core along with chlorophyll *c* and fucoxanthin. It is however present from ca. 1826 until ca. 1993. Phaeophorbide *a* also gradually declines to minimum values starting ca. 1972 until present.

Alloxanthin (Cryptophyta) is present in very small amounts from ca. 1804 until ca. 1948, where it exhibits a small peak and then abruptly increases from ca. 1984 until the

top of CCII. Hurley & Armstrong (1991) found that due to differential preservation throughout the water column, alloxanthin shows the best preservation in the surface sediments. This bias in preservation can often lead to an over representation of the pigment alloxanthin in comparison to the measured cryptophyte abundance in surficial sediment samples (Leavitt, 1993).

Beta-carotene, which is associated with green algae and higher plants and some photosynthetic bacteria, decreases from maximum amounts at ca. 1804 to its minimum at ca. 1961. Following that it only slightly increases but shows an overall decrease in the sediment core. With respect to pigment decay rates, β-carotene is the most stable carotenoid due to its lack of an epoxide functional group (Hurley & Armstrong, 1990).

Leavitt et al. (1989) found that elevated concentrations of lutein-zeaxanthin (Tracheophyta, Chlorophyta, Euglenophyta, & Cyanophyta), chlorophyll *a* (Plantae), and both phaeophytin *a* (chlorophyll *a* derivative) and phaeophytin *b* (chlorophyll *b* derivative) demonstrated an increase in chlorophyte and cyanophyte production. In Pine Lake, lutein-zeaxanthin remains fairly constant from the bottom of the core until the top. It reaches a maximum peak at ca. 1948 followed by a significant drop ca. 1961 recovering to its average abundance at the top of the core. Chlorophyll *a* and phaeophytin *b* follow this same pattern, overall maintaining a constant abundance. Phaeophytin *a* , although remaining relatively uniform in its presence, exhibits a maximum abundance where the other three pigments have shown rapid declines.

Diadinoxanthin, a diatom pigment, has a strong presence in the central core, demonstrating a slight increase from ca. 1801 to ca. 1993. It has been shown that many

diatom pigments, including diadinoxanthin, degrade faster than other pigments (Hurley & Armstrong, 1992). The high amounts of diadinoxanthin in CCII, indicates high diatom production occurred within the central sub-basin, which likely reflects eutrophic conditions (Züllig, 1989).

5.9 Anthropogenic Input on Historical Landscapes

Historically, palaeolimnological studies have concentrated on uncovering climate history. With an increase in human impact on the landscape, specifically lake systems, the focus has shifted to the use of palaeolimnology in tracing the effects of human impact on natural environments and then applying the historical findings to establish subsequent lake management programs. Recently, there has been an increase in the number of studies utilising lake sediments to gain a historical perspective both in Europe and North America.

5.9.1 Lough Augher, Northern Ireland

In Northern Ireland at Lough Augher, the palaeoecology of diatoms were used to study the effects of creamery effluent disposal (Anderson, 1989). Prior to creamery effluent, (ca. 1869 - 1900), a benthic assemblage of diatoms dominated, including species such as *Achnanthes minutissima*, *Fragilaria* spp., *Gomphonema* spp., *Navicula* spp., and *Cocconeis placentula*. The pre-creamery plankton representation was low and included *Stephanodiscus parvus*, *Asterionella formosa*, and *Diatoma tenue var. elongatum*. This particular assemblage is similar to the pre-European settlement diatom composition found in North American lakes (Bradbury, 1975; Engstrom et al., 1985).

There are several phases of change that occurred in the diatom community as a result of the onset of creamery effluent disposal. The first is the initial reaction to nutrient enrichment resulting in a shift of the diatom composition to a *Aulacoseira ambigua* dominated assemblage, with slightly smaller increases in *Asterionella formosa* and *Diatoma* in ca. 1917 (Anderson, 1989). The second phase is transitional, and represents ongoing nutrient enrichment, resulting in a diatom assemblage dominated by small, planktonic species such as *Stephanodiscus parvus* and *Cyclostephanos* spanning ca. 1940 to 1960. It has been noted by Reynolds (1984) that in a productive, eutrophic lake, the community response to continued increases in nutrient load is smaller and less dramatic after the initial impact. With the increase in phosphorous, there is a change in the Si:P ratio, allowing *S. parvus* to outcompete *A. formosa,* which has a requirement for Si in natural populations (Anderson, 1989). In ca. 1976, the creamery effluent was redirected elsewhere, coinciding with a rapid decline is *S. parvus* values. Since phosphorous concentrations, remained high, due to internal release of phosphorous from anoxic sediments, the deline in *S. parvus* is probably the result of a silica limitation (Anderson, 1989).

5.9.2 Foster Lake &Buck Lake, Yellowstone National Park

Engstrom et al. (1991) examined several lakes in the northern range of Yellowstone National Park to assess variations in sediment input and nutrient enrichment over the past 150 years. Each of the Yellowstone lakes displayed differing patterns of limnological change from the early 19th century to present day (Engstrom et al., 1991).

Localized factors played an important role in controlling diatom distribution and limnological history (Engstrom et al., 1991).

Over the past 150 years some distinct changes have occurred at Foster Lake. In the basal sediments (ca. 1845), the planktonic taxa dominate, including species such as *Stephanodiscus parvus*, *Stephanodiscus minutulus*, and *Cyclotella stelligera*. There were benthic and epiphytic taxa present in smaller quantities (*Amphora ovalis* var. *pediculus*, *Gomphonema dichotum*, *Cocconeis placentula* var. *lineata*, *Fragilaria pinnata*, and *Fragilaria brevistriata*). Early in the 19th century, Foster Lake appeared to be moderately rich in nutrients with the combined presence of *Stephanodiscus* sp. and *C. stelligera*. However, since the benthic taxa displayed a great diversity, water transparency must still have been high (Engstrom et al., 1991)

After ca. 1875, the planktonic taxa decline, beginning with a drop in *S. parvus* followed by *C. stelligera* and coincident increases in a variety of benthic taxa. The shift from planktonic to benthic dominance suggested higher water transparency and lower phosphorous and nitrogen concentrations or perhaps silica limitation. The chrysophyte cysts also increased at this time, suggestive of a superior competitive ability of the chrysophytes to diatoms during periods of low nutrient concentrations (Smol, 1985).

In the mid 1950s there was a short-lived increase in *Cyclostephanos invisitatus* and a coincident decline in the relative abundance of chrysophyte cysts. *C. invisitatus* is a common eutrophic taxa found during periods of low dissolved silica. Its increase is suggestive of a return to higher nutrient levels for a brief period (Engstrom et al., 1991). After the 1960s there was a return in dominance of benthic taxa. *Fragilaria* sp., which are

epiphytes, attained dominance in the mid-60s suggesting oligotrophic conditions and high water transparency (Brugam, 1980).

In comparison with Foster Lake, Buck Lake had a more stable diatom flora over the last two centuries. The diatom assemblage was dominated by *Stephanodiscus* sp. (*S. parvus*, *S. hantzschii*, and *S. minutulus*) and *Cyclostephanos invisitatus*, all of which are characteristic of eutrophic waters (Engstrom et al., 1991). Their high relative abundance is indicative of nutrient-rich conditions for at least 170 years, implicating a naturally eutrophic state prior to landscape management. Between the mid 1920s and the mid 1960s there is an expansion of *Fragilaria* sp. which prompted an increase in the proportion of benthic and epiphytic diatoms relative to planktonic species. After ca. 1960 towards present day, the diatom assemblage returns to the pre-1920 community, being dominated by planktonic, eutrophic diatom species. Geochemical evidence for greater eutrophy in Buck Lake is corroborated by the diatom data and coincides with a known increase in elk populations in the northern range during the last two decades (Engstrom et al., 1991).

The decline in planktonic taxa at Foster Lake and the brief expansion of benthic taxa at Buck Lake can be explained by a number of possibilities (Engstrom et al., 1991). This shift could result from a decline in lake level which would increase the littoral area for benthic diatoms and macrophytes. The dominance of benthic diatoms could also result from a decline in phosphorous, nitrogen or silica availability within the water column (Engstrom et al., 1991). Since benthic taxa can obtain silica from the sediments, they would have the competitive advantage over planktonic taxa when silica concentrations in

the water column are low.

Both Buck Lake and Foster Lake were clearly meso-eutrophic prior to park establishment, indicating that watershed input of nutrients to these systems has naturally been quite high (Engstrom et al., 1991).

5.9.3 Wood Lake & Charlie Lake, British Columbia

Reavie et al. (1995) examined several inland British Columbia lakes which were suspected of becoming mesotrophic or eutrophic as a result of anthropogenic activities. Wood Lake, located in the Okanagan Valley, has had its natural vegetation replaced by orchards, pasture land and summer houses. Leaking septic tanks and agricultural drainage were targeted as the primary sources of nutrient input to the lake. Prior to nutrient input (pre-20th century), sediments were dominated by a complex of planktonic diatoms such as *Aulacoseira ambigua*, *Aulacoseira subartica*, *Cyclotella ocellata*, *Cyclotella pseudostelligera*, and *Stephanodiscus minutulus*. In the early 1900s, there was a rapid decline in the cyst to diatom ratio, accompanied by a sharp rise in *S. minutulus* (Reavie et al., 1995). These changes coincided with the onset of lake deterioration due to agricultural development and inflow stream diversion for irrigation purposes (Reavie et al., 1995). After ca. 1958, both *S. minutulus* and diatom-inferred phosphorous declined, suggesting an improvement in water quality (Reavie et al., 1995). With the occurrence of anthropogenic nutrient enrichment, small *Stephanodiscus* species increased in relative abundance. When the drainage basin disturbances ceased, surface water quality improved and the eutrophic diatom species declined (Reavie et al., 1995).

Charlie Lake, located in Fort St. John, received nutrient-rich effluent from agricultural input and sewage disposal into the groundwater from domestic residences (Reavie et al., 1995). The result was dense blooms of *Aphanizomenon flos-aquae*, a blue-green algal species recognized as a eutrophic indicator. The diatom assemblage prior to twentieth century nutrient enrichment, was comprised of *Fragilaria pinnata*, *Aulacoseira ambigua*, and three *Stephanodiscus* species, all of which are indicative of a naturally productive system (Reavie et al., 1995). Between ca. 1873 to ca. 1991, *Stephanodiscus hantzschii* dramatically increased, accompanied by a slight increase in *Stephanodiscus parvus* (Reavie et al., 1995). At the same time there was a sharp decline in *F. pinnata* from a 48% relative abundance to a 7% relative abundance (Reavie et al., 1995). Due to the naturally high productivity of Charlie Lake, chrysophyte abundances were negligent. With the onset of deforestation, agricultural development and sewage disposal in the Charlie Lake region, the productivity, assessed through phosphorous concentration, of the lake showed signs of increasing (Reavie et al., 1995).

Between the study lakes, the responses varied relative to the hypothesis that nutrient input would increase as human population growth expanded in the watersheds of the study lakes (Reavie et al., 1995). It would also appear that lakes with large catchment areas were the most severely affected, notably Wood Lake and Charlie Lake (Reavie et al., 1995).

5.10 Pine Lake

Pine Lake shows both similarities and differences to other eutrophication studies. The first european settlers arrived at Pine Lake during 1890 and 1900, establishing a trading post and a post office, causing an overall increase in activity and land use surrounding the lake (Elnora Hist. Commit., 1972). During this time period, *Aulacoseira granulata* increased to become the dominant diatom species until ca. 1926 in the northern and southern sub-basins. With increased activity in the Pine Lake catchment it is probable that nutrient input became progressively higher. This would explain the presence of *A. granulata*, a eutrophic species often found in waters receiving anthropogenic input (Stoermer et al., 1981). At Lough Augher, the initial reaction to nutrient enrichment was a shift to an *Aulacoseira* dominated assemblage (Anderson, 1989). Charlie Lake and Wood Lake already had *Aulacoseira* as a dominant portion of the diatom assemblage, indicative that both systems were naturally productive (Reavie et al., 1995).

Prior to ca. 1926, there was a decline in *A. granulata* and subsequent replacement by *Cyclotella bodanica* aff. *lemanica* during a time period in which there was land clearing, burning, and abandonment around the Pine Lake region (Batchelor, 1978). The depression also occurred within this time frame, probably supressing agricultural growth thereby limiting the amount of nutrients going into Pine Lake.

In the 1940s, *A. granulata* started to resume dominance in the diatom assemblage at Pine Lake. The diatom to cyst ratio also started to increase, indicating a shift to a more eutrophic system. At Wood Lake, the cyst to diatom ratio rapidly declined coinciding with the onset of lake deterioration in the early 1900s (Reavie et al., 1995). At ca. 1935-

1940, the onset of recreational development is believed to have occurred at Pine Lake. This may have increased the nutrient load at this time. In CCII ca. 1948, there was a peak in calcium carbonate content which was also seen ca. 1940 at Wood Lake and was attributed to the intensification of pesticide and fertilizer use (Walker et al., 1993).

As water quality started to become a problem in the 1970s for Pine Lake residents (Sosiak & Trew, 1996), *C. bodanica* aff. *lemanica* virtually disappears in the three sub-basins. *C. bodanica* has been known to disappear as eutrophication progresses, being replaced by more eutrophic diatom species (Klee & Schmidt, 1987). After ca. 1972, myxoxanthophyll rapidly increases which could be indicative of increased blue-green algal populations consistent with eutrophic lake systems (Gorham et al., 1974).

Stephanodiscus parvus, *Asterionella formosa*, and *Fragilaria crotonensis* also exhibit peaks in the top portion of the Pine Lake cores. In Lough Augher, both *S. parvus* and *A. formosa* increased as a result of ongoing nutrient enrichment (Anderson, 1989). In both Charlie Lake and Foster Lake, with anthropogenic nutrient input there was an increase in small *Stephanodiscus* species (Reavie et al., 1995). *Stephanodiscus parvus*, does not reach the high relative abundance in Pine Lake that can be seen in other eutrophication studies. This may relate to the silica to phosphorous ratio. If it is high, *S. parvus* does poorly (Engstrom et al., 1991) whereas *A. granulata* grows efficiently (Anderson et al., 1990). *Fragilaria crotonensis* along with *A. formosa* show a peak between ca. 1984 and ca. 1993 in the southern sub-basin only. According to Watson (1993), the blue-green algal community became dominant in the central station by the early summer of 1992 and remained dominant until the late fall of the same year. Since *F.*

crotonensis is a late summer and fall blooming species it would be outcompeted in high phosphorous to nitrogen conditions which favor blue-green algal development (Bradbury & Waddington, 1973; Watson, 1993).

6. CONCLUSIONS

Pine Lake is one of Alberta's most intensively developed lakes. The increase in anthropogenic stress through time is reflected in the diatom record of the lake. Seven sediment cores were taken from the three sub-basins in Pine Lake. Diatom trends within the cores were correlated using non-parametric statistics on an interval-by-interval basis. Both the Kendall Coefficient of Concordance and the Mann-Whitney test were utilized. The results show a significant similarity within each sub-basin and between the three sub-basins in the diatom composition. This suggests that a single sediment core provides an accurate representation of historical change in Pine Lake.

With the increase in human activity and land use in the Pine Lake catchment, the diatom assemblage has shifted from an oligotrophic/mesotrophic lake (dominated by *Cyclotella bodanica* aff. *lemanica*) before European settlement to a eutrophic lake (dominated by *Stephanodiscus parvus* and *Aulacoseira granulata*). At present, Pine Lake is characterized by high concentrations of chlorophyll *a* occurring during midsummer. There are relatively few diatom species that comprise the Pine Lake assemblage, which is consistent with other eutrophic lake systems. Blue-green algae are found in exceedingly high numbers, due primarily to high concentrations of phosphorous in the water column, and low dissolved oxygen concentrations occurring just above the sediment/water interface. Water quality decreased drastically between 1978 and 1984 despite rising water levels. The phosphorous contributing to poor water quality is thought to be derived from agricultural runoff and septic system input from both commercial and residential developments. With the nutrient enrichment the blue-green algal population has increased

and can be seen with the rapid increase of myxoxanthophyll from ca. 1970 to present.

Overall, Pine Lake has undergone considerable change as a result of anthropogenic impact. The results of this thesis show clearly that anthropogenic stress on the lake catchment has led to an increase in nutrient input into Pine lake which can be detected through the diatom record.

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Appendix I: Diatom Taxonomy, Habitat Preference, and Nutrient Preference

In the 7 sediment cores (SCI, SCII, SCIII, NCI, NCII, CCI, CCII) the following genera of diatoms were identified down to variety and occurred in >1% atleast once throughout any given sediment core.

DIATOM TAXONOMY	HABITAT PREFERENCE	NUTRIENT PREFERENCE
Achnanthes lanceolata (Brébisson) Grunow	Epipelic	Mesotrophic
Amphora libyca Ehrenberg	Epipelic	Cosmopolitan
A. ovalis (Kützing) Kützing	Epipelic	Mesotrophic
A. pediculus (Kützing) Grunow	Epipelic	Mesotrophic
Asterionella formosa Hassall	Planktonic	Cosmopolitan
Aulacoseira granulata (Ehrenberg) Simonsen	Planktonic	Eutrophic
Cocconeis placentula var. *placentula* Ehrenberg	Epiphytic	Cosmopolitan
Cocconeis placentula var. *euglypta* (Ehrenberg)Grunow	Epiphytic	Cosmopolitan
Cocconeis placentula var. *klinoraphis* Geitler	Epiphytic	Cosmopolitan
Cocconeis placentula var. *lineata* (Ehrenberg)Van Heurck	Epiphytic	Cosmopolitan
Cyclotella bodanica aff. *lemanica* (O.Müller ex Schröter) Bachmann	Planktonic	Mesotrophic
C. meneghiniana Kützing	Planktonic	Mesotrophic
Epithemia adnata (Kützing) Brébisson	Epipelic	Mesotrophic
E. argus (Ehrenberg) Kützing	Epipelic	Mesotrophic
E. frickei Krammer	Epipelic	Mesotrophic

Epithemia turgida (Ehrenberg) Kützing	Epipelic	Mesotrophic
Fragilaria brevistriata Grunow	Epipelic	Cosmopolitan
F. capucina Desmazières	Epiphytic	Eutrophic
F. capucina var. *mesolepta* (Rabenhorst) Rabenhorst	Epiphytic	Eutrophic
F. capucina var. *vaucheriae* (Kützing) Lange-Bertalot	Epiphytic	Eutrophic
F. construens (Ehrenberg) Grunow	Epipelic	Cosmopolitan
F. construens f. *binodis* (Ehrenberg) Hustedt	Epipelic	Cosmopolitan
F. construens f. *venter* (Ehrenberg) Hustedt	Epipelic	Cosmopolitan
F. crotonensis Kitton	Planktonic	Cosmopolitan
F. leptostauron (Ehrenberg) Hustedt	Epipelic	Cosmopolitan
F. leptostauron var. *martyii* (Héribaud) Lange-Bertalot	Epipelic	Cosmopolitan
F. pinnata Ehrenberg	Epipelic	Cosmopolitan
F. pinnata var. *pinnata* Ehrenberg	Epipelic	Cosmopolitan
Gomphonema species	Epiphytic	Cosmopolitan
G. acuminatum Ehrenberg	Epiphytic	Meso-Oligo
G. affine Kützing	Epiphytic	Eu-Meso
G. augur Ehrenberg	Epiphytic	Cosmopolitan
G. clavatum Ehrenberg	Epiphytic	Cosmopolitan
G. gracile Ehrenberg	Epiphytic	Meso-oligo
G. insigne Gregory	Epiphytic	Cosmopolitan
G. minutum (C. Agardh) C. Agardh	Epiphytic	Cosmopolitan

G. minutum f. *lemanese* Lange-Bertalot & Reichardt	Epiphytic	Cosmopolitan
G. minutum f. *pachypus* Lange-Bertalot & Reichardt	Epiphytic	Cosmopolitan
G. minutiforme Lange-Bertalot & Reichardt	Epiphytic	Cosmopolitan
G. occultum Reichardt & Lange-Bertalot	Epiphytic	Cosmopolitan
G. olivaceum (Hornemann) Brébisson	Epiphytic	Eutrophic
G. olivaceum var. *balticum* (Cleve) Grunow	Epiphytic	Eutrophic
G. parvulum (Kützing) Kützing	Epiphytic	Cosmopolitan
G. pumilum (Grunow) Reichardt & Lange-Bertalot	Epiphytic	Cosmopolitan
G. sarcophagus Gregory	Epiphytic	Cosmopolitan
Navicula cari Ehrenberg	Epipelic	Cosmopolitan
N. scutelloides W. Smith ex Gregory	Epipelic	Cosmopolitan
Nitszchia species	Epipelic	Cosmopolitan
N. filiformis (W. Smith) Van Heurck	Epipelic	Cosmopolitan
N. frustulum (Kützing) Grunow	Epipelic	Cosmopolitan
N. inconspicua Grunow	Epipelic	Cosmopolitan
N. leistikowii Lange-Bertalot	Epipelic	Cosmopolitan
N. palea (Kützing) W. Smith	Epipelic	Cosmopolitan
Nitszchia paleacea (Grunow) Grunow	Epipelic	Cosmopolitan
N. pura Hustedt	Epipelic	Cosmopolitan
N. supralitorea Lange-Bertalot	Epipelic	Cosmopolitan

N. wuellerstorftii Lange-Bertalot	Epipelic	Cosmopolitan
Stephanodiscus niagarae Ehrenberg	Planktonic	Eutrophic
S. parvus Stoermer & Håkansson	Planktonic	Eutrophic

Appendix II: Mann-Whitney Non-Parametric Test

The actual measurements are not used, instead ranks of the measurements are employed (Zar, 1984). The Mann-Whitney statistic is,

$$U = n_1 n_2 + \frac{n_1 (n_1 + 1)}{2} - R_1$$

$$U' = n_1 n_2 - U$$

Sample Calculation:

H_0 = Core 1 and Core 2 diatom counts are the same.
H_A = Core 1 and Core 2 diatom counts are not the same.

Level of Significance = 0.05

Species chosen for ranking in all cores are:

Cyclotella bodanica aff. lemanica
Aulacoseira granulata
Stephanodiscus niagarae
Stephanodiscus parvus
Fragilaria construens (& varieties)
Asterionella formosa
Amphora pediculus

At 0cm depth:	North Core I		North Core II	
	% abundance	Rank	% abundance	Rank
S. parvus	14.29	4	14.71	3
A. formosa	13.72	5	8.76	6
A. granulata	52.26	2	59.02	1
C. bodanica	0.56	11	0.35	12.5*
S. niagarae	3.20	7	2.80	8
A. pediculus	1.50	9	0.35	12.5*
F. construens	0.94	10		
	$n_1 = 7$	$R_1 = 48$	$n_2 = 6$	$R_2 = 43$

* The twelfth and the thirteenth values are tied at 0.35%, so they are each assigned the rank of (12 + 13)/2 = 12.5.

U = 22
U' = 20
$U_{0.05\,(2),\,6,\,7} = 31$

U(22) is less than the critical value (31), therefore the null hypothesis (H_0) is accepted. 109 CCI and CCII at depth 0 are similar enough to be condsidered the same in the ranking of the diatom species.

The actual measurements are not used, instead ranks of the measurements are utilised. First, set up a k x N table, where k is equal to the number of sets of ranking (cores) and N is the number of individuals (diatom species) ranked. Find the sum of the ranks (R_j) in each column of the above table. The mean value of R_j is then calculated by summing R_j and dividing by N. Each of the R_j values can then be expressed as a deviation from the mean value. These mean values are then summed and squared to give us 's'. From there, W (coefficient of concordance) can be calculated using the following formula,

$$W = \frac{s}{1/12\ k^2(N^3 - N)}$$

where, $s = \sum (R_j - \sum R_{jN})^2$

$1/12\ k^2(N^3 - N)$ = maximum possible sum of the squared deviations

Testing for the significance of W, with N = 7, requires comparing observed 's' values with critical values. If observed 's' is equal to or greater than the critical value at a particular level of significance then H_o is rejected. Where H_o, the null hypothesis, is that the core diatom species abundances are unrelated to each other.

Sample Calculation:

SCI, SCII, SCIII at depth 5.0cm
The same 7 diatom species were ranked for all calculations.

Core	A	B	C	D	E	F	G
SCI	1	4	5	2	6	3	7
SCII	1	5	2	3	6	4	7
SCIII	1	2	5	3	6	7	4
R_j	3	11	12	8	18	14	18

A - *Aulacoseira gramulata*
B - *Cyclotella bodanica* aff. *lemanica*
C - *Stephanodiscus niagarae*
D - *Stephanodiscus parvus*
E - *Amphora pediculus*
F - *Asterionella formosa*
G - *Fragilaria construens* (& varieties)

where k = 3 and N = 7

mean $R_j = 3 + 11 + 12 + 8 + 18 + 14 + 18 /7$

mean $R_j = 12$

$s = (3-12)^2 + (11-12)^2 + (12-12)^2 + (8-12)^2 + (18-12)^2 + (14-12)^2 + (18-12)^2$

$s = 174$

$W = 0.69$

At 0.05 level of significance,

W critical value is .624

$W_{observed} > W_{critical}$

Therefore, H_o is rejected, SCI. SCII, SCIII are correlated.

Appendix IV: Pigment Calculations

Sample Calculation: South Core II, 0cm, chlorophyll c

let chlor c = chlor c(peak area) x ratio

Ratio:

expect = (slope of calibration curve) x injection amount - intercept

= 4954.55 x 80 - (-15865.55)
= 412229.55

ratio = expect / standard peak area

= 412229.55 / 396207
= 1.04 (note: if ratio <1, let ratio = 1.0)

then,

chlor c = chlor c peak area x ratio

= 241991 x 1.04
= 251670.64

Concentration of chlorophyll c:

chlor c = (pigment x slope) x (total vol.dilution/injec.vol)/
(extract x %OM / 100) x 1e3/
gram molecular weight of pigment x 1e3

= (251670.64 x 0.303e-6) x (500/80)/
(.04510g x 37.5/100) x 1e3/ (610 x 1e3)

= 1.719 x 1e4 nmol/L of chlorophyll c at Ocm depth